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NAVY SATELLITE COMMUNICATIONS
IN THE HELLENIC ENVIRONMENT

by

Athanasios Economou

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Navy Satellite Communications in the Hellenic Environment

by

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requirements of the degree of

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This thesis covers the history of satellite communications from its beginning in 1957 until recent years, describes the space subsystem and explains the major components of satellite communications. It defines the practical problems of satellite communications such as radiation and frequency dependence attenuation. It also examines certain aspects of satellite communications in the Hellas environment including reliability and survivability in a hostile environment. The last chapter outlines the major decisions and evaluation required for a tactical satellite system for the Hellenic Navy.

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I. SATELLITE COMMUNICATIONS

A. INTRODUCTION

In the short period of time since the introduction of the first operational system in 1965, satellite communications have changed the entire nature of communications.

In the international area, the traffic is dominated by voice, and the links to more than 100 countries have had a major impact on the communication patterns of both business and military. This happened because radio has evolved from an experimental curiosity to a definite necessity.

At the same time the demand made on the techniques and capabilities of communications have increased enormously. A world population once separated by weeks or months is now only seconds apart via communication links.

Experience over the past 20 years has shown that the usage rate of both commercial and military systems increases by approximately 10 percent per year [Ref. 1]. Also, when an improved service is offered, the traffic tends to increase. An example of the latter is the increase in the number of long distance calls

following the introduction of direct distance dialing service.

In the military area during the recent decades, only the United States and the Soviet Union have been able to take full advantage of this communication potential. But early in the next century, space platforms are likely to bring about a revolution in Naval warfare that will rival the importance of steam propulsion, the submarine, or the introduction of aircraft into operations at sea.

Space sensors from research facilities around the world will, within 20 years, make it possible to detect and track ships anywhere day or night, in all but the worst weather.

At present, seven nations--United States, Soviet Union, Britain, China, France, Japan, India--have launched satellites using indigenous technology.

A dozen other countries, including high--technology nations such as West Germany, hustling newcomers like Brazil, and relatively low--technology ones such as Indonesia have space programs in progress or are purchasing space hardware from others.

Satellite communications have become a vital part of strategic and tactical systems, and current plans project an even larger role in the future. In the

mobile area, reliable satellite communications to ships are now available on a worldwide basis.

Current satellite communications have three tactical weaknesses that can be resolved by new technology: (1) geostationary satellites (in orbit high above the equator) provide unreliable service above 60 degrees latitude, (2) communication satellites are vulnerable to jamming by anyone within their extensive field of view (approximately a quarter of the earth's surface for a current geostationary satellite), and (3) submarines currently must approach the surface to use satellite communications [Ref. 1].

Satellite communication systems have several unique properties which distinguish them from terrestrial communication systems.

The main ones are:

1. The broadcast property. A satellite transmission can, in principle, be received at any point within its coverage area which has a number of implications. This means that any location, if suitably equipped, could eavesdrop on information intended for someone else with potentially serious consequences with sensitive information. Under these conditions, information in both commercial and military systems is vulnerable to unauthorized access. To prevent this unauthorized

access, cryptographic equipment has been developed and is available for each customer.

2. Geographical flexibility. The advantage of satellite communications is that it can reach locations either lacking in or remote from terrestrial services. Some times it can be the most economic route.

3. Distance--Insensitive cost. Whereas the cost of building and maintaining terrestrial transmission facilities is directly proportional to the length of the circuit or transmission route, this is not so for satellite services. Satellite information travels through a free space and therefore the cost is almost independent of distance.

4. Transmission capacity and speed. Transmission capacity in terms of the amount of information that the satellite is capable of handling per unit of time is determined largely by its design and by the methods employed for impressing information onto the radio frequency link. The range of transmission speed available to the user depends upon such factors as the types of traffic for which the system was designed and the form in which the services are marketed.

5. Transmission delay and echo. Transmission delay: Traveling at the speed of light, a piece of information takes about 270 milliseconds to complete the round trip of 44,500 miles from earth to a

geostationary satellite and back. When allowances are also made for associated processing on-board the satellite and at the earth terminals, transmission delay is of the order of 320 milliseconds. The echo effect: The effect where the speaker hears the echo of his own voice which is caused by the presence of both two--wire and four--wire circuits and the transition between the two.

B. OBJECTIVES

The underlying purpose of this thesis is to analyze a basic UHF satellite system.

Primary emphasis will be on evaluating the system and how effective, reliable, and survivable it will be in a stressed environment.

The specific subobjectives are as follows:

1. Would a satellite communication system in the Hellenic environment provide security and survivability?

2. Would the security, survivability, and the legal--regulatory ramification of a commercial satellite system provide an available nationwide, emergency military satellite communication network?

3. Economic evaluation of an active satellite system.

4. A military satellite communication system should provide a jamming resistant mode. What are the specifications for a capable system?

5. Is an active UHF satellite communication system the best solution for the Hellenic Navy?

C. HISTORY OF SATELLITE COMMUNICATIONS

The USSR successfully launched the first manmade earth satellite on 4 October 1957, which was called SPUTNIK. This demonstrated man's ability to place objects into an orbit around the earth and brought to fruition a long nurtured ambition. The tremendous potential of the specialized field of a satellite communication system was created.

On 18 December 1958, the Signal Corps Orbiting Relay (SCORE) communication satellite was successfully launched by the U.S. Army. As a practical demonstration of its capability, President Eisenhower recorded a Christmas message which was rebroadcast to the world via the satellite. SCORE operated for 12 days, during which time 97 contacts were made. SCORE was designed to receive message traffic as it passed over one station, record it, and retransmit the traffic as it passed over another station. This method of recording messages for later transmission is known as the store and forward technique. Its capacity was one

voice channel or seven 60 words per minute (wpm) teletype channels.

The first real communication satellite was ECHO--I which was launched by the United States National Aeronautics and Space Administration (NASA) on 12 August 1960. This satellite was a sphere 30 meters in diameter weighing 75.5 kg and was a spherical pressurized balloon with an envelope of plastic mylar and aluminum. Its communication capabilities were for a voice baseband bandwidth of 200 Hz to 3000 Hz and for music 30 Hz to 15000 Hz.

ECHO--II was a bigger and stronger successor. It was launched on 25 January 1964, and the shape and communication capabilities were the same as ECHO--I. The ECHO satellite series consisted of passive reflectors only. The main advantage of a passive satellite is the almost infinite capacity for simultaneous multiple communication links. The serious disadvantage is the inefficient use of transmitter power. In ECHO satellite operations, only one part in 10^{18} of transmitted power was returned to the receive antenna.

The formula for carrier power received, C, at the earth station and for an active satellite is

$$C = \frac{Pt\ Gt\ Ar}{4\pi R^2\ L}$$

where Pt = Satellite transmitter power

Gt = Transmitter gain

Ar = Earth station antenna effective area

Ar = Gr (lambda)^2 / 4π

lambda = wave length (c/f)

where f = Frequency in Hertz

c = Velocity of wave propagation in free space is 2.998 x 10^8 m/s

Gr = Receiver gain

L = Path loss

R = Distance between satellite--earth stations

In passive satellites the R^2 in the denominator is R^4. This inverse fourth power law requires very large antennas on ships.

COURIER was an experimental satellite which demonstrated the feasibility of using active repeater satellites for delayed message transmission. The first satellite was launched on 18 August 1960, weighted 500 pounds with 300 pounds of communications equipment on board including five tape recorders (four digital, one analog), a telemetry generator, VHF duplexer, command decoder, and spares. The communication capacity enabled COURIER to simultaneously transmit, receive, and store 68,000 digitally encoded words per minute. The tape recorders aboard the satellite stored messages from the ground stations and upon command, the

satellite re--transmitted the message to another ground station.

The COURIER satellite carried a standard VHF beacon to permit tracking by the existing worldwide network of satellite tracking stations in order to provide an ephemeris for use by the carrier ground stations. The ephemeris furnished to each ground station gives a series of antenna azimuth and elevation pointing angles plotted over discrete time intervals for each pass of the satellite over a ground station. For ease of acquisition, the ground station transmits the initial turn--on command via the UHF (1750 MHz) link. Further exchanges of message traffic and commands are accomplished over the microwave link with the satellite. Telemetry data are transmitted from the satellite to the ground stations over the VHF link.

All the communication satellites launched currently are active satellites, which generally contain an antenna for picking up the signal from the earth, an amplifier for strengthening the signal, and a transmitter for sending it back.

The first active communication satellite made in the United States was launched at Cape Canaveral, Florida, on 10 July 1962 and called TELSTAR--I. It was developed by AT&T (American Telephone and Telegraph). It contained a receiver, amplifier, and transmitter for

relaying messages plus a beacon transmitter to help earth stations locate its position. It also carried an extra antenna for receiving control signals from the earth. The communication capacity was one television channel, 600 simplex telephone channels, and 12 duplex telephone channels. Transmission frequencies in the 6/4 GHz range were used and the single transponder was 2 watts. TELSTAR--I made the first trans--atlantic transmission of TV and voice communications using a communication satellite. It continued to operate successfully until 23 November 1962, when a failure occurred in one of the transistors in a circuit used to control the satellite's radio equipment.

TELSTAR--II replaced TELSTAR--I, and was launched on 21 January 1964 in an orbit with a maximum altitude of 6360 miles instead of 3531 which was used for TELSTAR--I. It operated successfully until an undetected failure caused it to cease operation in July 1964.

Another experimental satellite, RELAY--I was launched on 13 December 1962 and was the first communication satellite designed to link North America, South America, and Europe. Its communication capacity was 1 television program or 12 full--duplex telephone/data/facsimile channels or 1 simplex telephone/data/facsimile channel.

The next series of communication satellites were called SYNCOM or synchronous communication satellites. By synchronous satellite we mean a satellite which is stationary with respect to the earth or one that has a 24 hour nonequatorial orbit. A synchronous or geostationary satellite orbits the earth at a speed of 11,068.8 km/h. At this velocity the satellite makes one revolution around the earth in exactly the same amount of time it takes the earth to rotate once on its axis. The only great circle that is moving exactly parallel to the direction of the earth's rotation is the equator. The geostationary orbit lies in the equatorial plane at a distance of approximately 42,164.2 km from the earth's center. Because the earth's radius is 6378.155 km, the distance between the point where the equator meets the line joining the center of the earth and the satellite is 35,784.045 km.

SYNCOM I, II, and III were launched on 14 February 1963, 26 July 1963, and 19 August 1964 respectively. Each satellite was 71 cm in diameter, 39.4 cm in height and weighed 39 km.

SYNCOM--I was the first communication satellite designed to provide communication services while operating at synchronous altitude. The communications suit was redundant, employing frequency translations and was capable of one two--way telephone, and sixteen

teletypes, or one TV channel. The dual uplink frequencies were near 7.362 GHz and the single downlink frequency was 1.815 GHz. The launch was successful but the satellite failed to perform in orbit.

SYNCOM--II was launched on 26 July 1963 and after much maneuvering was placed into a synchronous but not stationary orbit over Brazil. To remain stationary it would have to be over the equator. This satellite was used to relay a telephone call on 9 August 1963 from California to Africa, a distance of 7,700 miles and was the longest satellite point to point communications made to that date.

SYNCOM--III was orbited on 19 August 1964 and became the first satellite to be placed into geostationary synchronous orbit when finally positioned over the Pacific Ocean. SYNCOM--III was entirely successful and was used to relay coverage of the 1964 Olympic Games from Tokyo to California.

Synchronous satellites are desirable for both TV relay and broadcast service. Their high altitude gives large earth surface area coverage and their fixed position improves the quality of signals received. The principal advantages of a satellite in synchronous or geostationary orbit are the following:

1. The satellite remains stationary with respect to one point on earth and therefore the earth station is not required to constantly track the satellite. Instead, the earth station antenna beam can be accurately aimed toward the satellite by using the elevation angle and the azimuth angle. This reduces the station's cost considerably.

2. With a 5 degree minimum elevation angle of the earth station antenna, one geostationary satellite can cover almost 38% of the surface of the earth.

3. Three geostationary satellites (120 degrees apart) can cover the entire surface of the earth with some overlapping, except for the polar regions above latitudes 76° N and 76° S, assuming a 5 degree minimum elevation angle.

4. The doppler shift caused by a satellite drifting in orbit (because of the gravitational attraction of the moon and the sun) is small for all the earth stations within the geostationary satellite coverage. This is desirable for many synchronous digital systems. [Ref. 2]

As satellite costs dropped from their initially high levels, it was quickly realized that they could compete with the world's suboceanic cables. In 1964 a number of countries signed an agreement to establish a worldwide international satellite communication

service. This was the beginning of the INTELSAT organization.

INTELSAT holds the monopoly for the provision of international public and private transmission services over satellite links. It also leases satellite capacity to a number of countries for their domestic use, and a growing number of national and regional services also lease capacity from INTELSAT. The following statistics illustrate the global importance of INTELSAT [Ref. 3].

Number of countries : 106

Satellites in orbit : 16

Operational earth stations : 216 (at 156 locations in 136 countries).

Since it commenced activities, INTELSAT has commissioned six classes of satellites, starting with INTELSAT--I and the latest, INTELSAT--VI, which became operational in 1986. A brief description of each class or series is given next.

On 6 April 1965 the small, but now legendary Early Bird Satellite (INTELSAT--I) was brought on station over the Atlantic. It handled 240 telephone channels, or one TV channel. Like all satellites in the series, Early Bird was spin stabilized. It was equipped with a non-directional antenna that transmitted radiation in

all directions, so that a major part of the radiated power was lost to space.

The INTELSAT--II series had much in common with their predecessor. The principal innovation lay in the introduction of a multiple--access technique which enabled all connected earth stations to converse simultaneously. This technique became available from 1967 onwards with three satellites in orbit.

The first INTELSAT--III made its appearance in 1968. The major innovation was the incorporation of a contra--rotating directional antenna. This device concentrated the power in the direction of earth and by rotating the antenna assembly in a direction opposite to that of the satellite body, the pointing direction remained fixed relative to earth.

The eight satellites in the INTELSAT--IV series were also characterized by a large increase in capacity. This was achieved through increasing the number of transponders and adopting a new antenna configuration. Each satellite had four antennas, providing hemispherical coverage and two spot beams. The direction of each spot beam antenna could be changed by remote control from earth, depending upon demand and traffic density.

INTELSAT--IV--A was a series of eight additional satellites developed from INTELSAT--IV. The major innovation was a complex antenna configuration which separated the spot beams serving the eastern and western hemispheres. This enabled the 6/4 GHz frequency band to be used twice over without mutual interference. Thus with no significant increase in satellite payload it was possible to increase capacity without utilizing new frequency bands, or employing a duplicate operational satellite. This series was launched in 1975 with each satellite having a capacity for 6000 telephone channels plus 2 TV channels and had a scheduled life of 7 years.

In 1980, the INTELSAT--V class of satellites was launched. This class operates in the 14/12 GHz range (Ku--Band) in addition to the 6/4 GHz (C--Band). This innovation basically made it possible to double the telephone channel capacity to 12,000.

The latest series is the INTELSAT--VI. The first 6 satellites in this class have an individual capacity of 40,000 telephone channels plus 4 TV channels. There are 50 transponders on each satellite. The first of the series was launched in 1986 with a schedule life of 10 years.

The International Maritime Satellite organization, INMARSAT, was started in 1982 with a relatively small membership but quickly expanded to have a wide international membership. It currently has over 40 members including Eastern European countries such as the USSR. INMARSAT is owned by INTELSAT and has its headquarters in London. In its initial years, INMARSAT used transponders on various satellites available from INTELSAT, the European Space Agency (ESA) with its MARECS satellite, and the MARISAT Joint Venture providing the MARISAT satellite. In 1982 INTELSAT--V was the first of a series launched with a MCS (Maritime Communication Subsystem) specifically for INMARSAT.

INMARSAT's primary mission is to provide a communication service to ships and mobile platforms. By July 1984, more than 2600 ships were equipped with shipboard satellite terminals. The service includes low rate (2.4 kbs) and high rate (up to 56 kbs) data, voice, and emergency services. During mid--1983, INMARSAT launched an ambitious plan to procure a world--wide satellite system for most remote mobile platforms and appeared to be offering the potential of an air traffic communications and control service. This second generation system is due to come into service in 1988. All delivered satellites are required to be compatible not only with the US launch vehicles and the

European launch vehicle, Ariane, but also with the Proton launcher of the USSR.

Another international organization which provides telecommunication services by satellite is called EUTELSAT. By 1983 EUTELSAT consisted of 20 EUROPEAN member countries who are represented through their telecom administrations.

The EUTELSAT satellites are used for main route telephony in Europe, TV distribution services, and exchange of TV programs within the European Broadcasting Union (EBU). In addition, special services (satellite multiservice system) are provided for the purpose of data transmission and teleconferencing required by the international business community, using small dish terminals.

The European program started with an experimental satellite--OTS--and moved to the operational phase with the launching in June 1983 of EUTELSAT--I. A EUTELSAT--I satellite with a satellite multiservice system payload was launched in August 1984. EUTELSAT is now considering the implementation of a three--satellite space segment, as opposed to the two-satellite configuration originally envisaged. From the beginning of the next decade, the EUTELSAT--I satellite will be replaced gradually by a newly designed Experimental Communication Satellite (ECS--A).

D. SUBSYSTEMS

When we refer to a communication satellite system we mean a large number of complex and interrelated subsystems. There are numerous different system specifications that can be combined (for example, orbit amplitude, shape and inclination, operating frequency and bandwidth, satellite specifications etc.). For each system characteristic there is a system design which arises from an examination of the interrelations between, and the choice of, a set of subsystems to optimize in some sense the resulting system.

The criteria that we use in order to categorize a satellite system can be either by technical characteristics or by operational uses. The latter seems more natural, and indeed, is instructive in the sense that after having categorized the satellites operationally we can examine the diversity of technical methods to achieve similar operational results.

A communication satellite system consists of the following subsystems.

1. Communication Satellite

Among the space subsystems, the satellite is the vital part. The two key attributes of most current and planned communication satellites are a geostationary orbit and the satellite acting as a relay

or repeater station. If a satellite at a particular height above the equator moves at the correct speed, it will travel once around the earth in the same time that the earth takes to complete one rotation. Also if it travels in the same direction as the earth it remains over the same point on the equator and appears stationary to an observer on the ground.

A geostationary satellite is visible from slightly less than one-half of the earth's surface. In fact only three satellites in orbit located at the vertices of an equilateral triangle with sides 88,000 km are sufficient to give nearly total coverage of the globe. Excluded are the polar regions above latitudes 75°N and the polar regions above latitudes 75°S, assuming a 5° minimum elevation angle.

Coverage angle and slant range: The total area of the earth seen by the satellite at any instant, or reciprocally the area from which the satellite is visible from the surface of the earth is bounded by a circle the radius of which is a function of satellite altitude H and minimum allowable earth antenna elevation angle E.

The earth coverage angle 2a max is the total angle subtended by the earth as seen from the satellite. This angle is important in the design of a global coverage antenna and depends on the satellite

altitude.

The coverage geometry is illustrated in Figure 1.1 [Ref. 2].

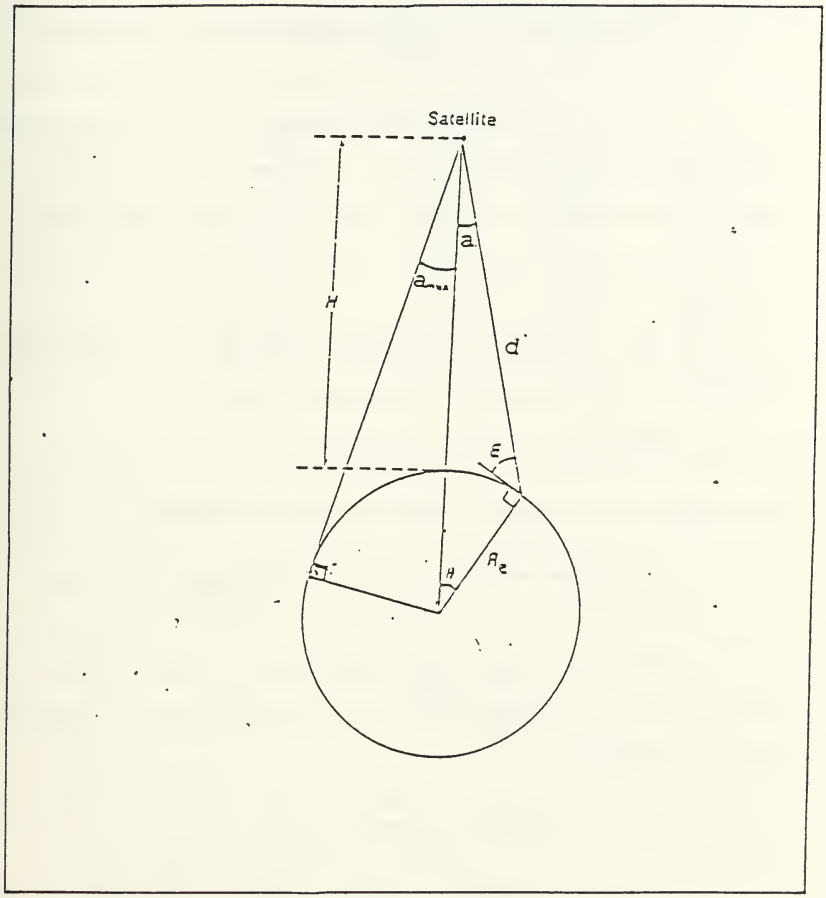

Figure 1.1 Coverage Geometry

For an elevation angle E of the earth station antenna, the communication coverage angle 2a is given by the relation:

$$2a = 2 \sin^{-1} \left(\frac{Re}{Re+H} \cos E \right)$$

For a geostationary orbit H = 35,786 km and the radious of earth Re is assumed to be about 6,378 km. By setting $E = 0^{\circ}$ the earth coverage angle is:

$$2a_{max} = 17.4^{\circ}$$

The central angle θ, which is the angular radius of the satellite footprint is:

$$\theta = 180-(90 + E + a) = 90 - E - a$$

and the slant range d can be determined as

$$d^2 = (Re + H)^2 + Re^2 - 2 Re (Re + H) \cos \theta$$

The coverage or spherical area Ae of the earth's surface within the visibility cone of angle 2a max is given by

$$Ae = 2\pi Re^2 \left(\frac{H}{Re + H} \right)$$

The percentage of the earth's surface visible from a satellite at any altitude is shown in Table I for several values of E.

TABLE I

EARTH'S SURFACE VISIBLE FROM A SATELLITE

HEIGHT		PERCENTAGE OF AREA VISIBLE		
Kilometers	Statute miles	a = 0 %	a = 7.5 %	a = 10 %
1,850	1150	11.5	7.7	6.70
3,700	2300	18.4	13.6	12.50
7,400	4600	26.9	21.3	19.80
11,100	6900	31.8	25.9	24.25
14,800	9200	34.9	28.8	27.15
18,500	11,500	37.2	31.1	29.20
22,200	13,200	38.8	32.5	30.70
25,900	16,100	40.1	33.8	31.90
29,600	18,400	41.1	34.8	32.85
33,300	20,700	41.9	35.6	33.65
35,900	22,300	42.4	36.1	34.00
37,600	23,400	42.5	36.2	34.10

A worldwide line--of--sight coverage pattern using four geosynchronous satellites is shown in Figure 1.2

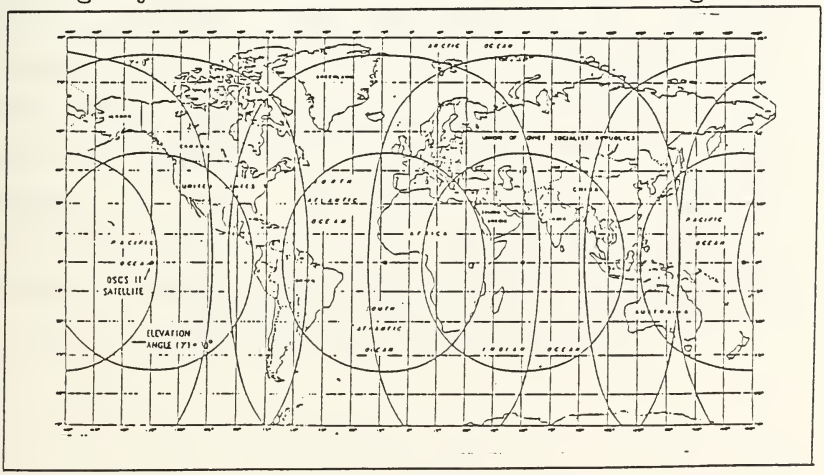

Figure 1.2 Worldwide line--of--sight

2. Communication Repeater

The communication repeater which is an interconnection of many channelized transponders generally consists of the following modules [Ref. 4]:

a. A wideband communication receiver/downconverter

b. An input multiplexer

c. Channelized Traveling Wave Tube Amplifiers (TWTAs)

d. An output multiplexer

A repeater with frequency translation and Traveling Wave Tube Amplifier (TWTA) is the most commonly used configuration on board a spacecraft. The repeater is usually transparent to the signal transmitted from the earth station, with the uplink frequency being higher than the downlink frequency. This frequency difference minimizes interference between the transmitted and received signal. Occasionally the various transponders of the repeater are configured in a way to optimize the communication links for the expected mode of access by earth stations. Each transponder may be accessed simultaneously by many carriers, with each carrier operating at a different frequency in what is known as Frequency Division Multiple Access (FDMA).

Alternatively, each carrier may access the whole transponder for a short period of time specifically allocated to the carrier, in what is known as Time Division Multiple Access (TDMA).

In contrast to the transparent or "passive" types, repeaters with signal--processing capability can be used. The on board processing of the received signal takes place at Radio Frequency (RF) level, Intermediate Frequency (IF) level, or at baseband. On board switching usually is done at RF level by an RF switch matrix that interconnects each received signal to the desired output port.

The wideband communication receiver/ downconverter is designed to operate within the 500 MHz bandwidth allocated for C--Band (5.9 to 6.4 GHz) and Ku--Band (14 to 14.5 GHz) uplink signals. The uplink signals are first filtered by a waveguide bandpass filter with approximately a 600 MHz bandwidth. They are then amplified by a parametric or a solid--state gallium arsenite field effect transistor (GaAs FET) low--noise amplifier with a typical noise figure of 2 to 4 dB. The amplified signals are then passed through a ferrite isolator to the input multiplexer.

3. Spacecraft Antennas

The satellite antenna is characterized by its frequency, bandwidth, polarization, gain, and beamwidth. The gain and beamwidth are related. The gain increases with the size of the antenna and the beamwidth decreases at the same rate. The most commonly used spacecraft antenna is the parabolic dish for area coverage. From synchronous altitude, the maximum beam width that one can use is approximately 17.4° for a "global beam" [Ref. 4]. Multiple antenna beams are increasing in importance because of the need to concentrate energy toward different parts of the world simultaneously. They are also attractive from the view point of frequency reuse, i.e., transmitting different message groups on the same frequencies, but beaming the groups simultaneously in different directions toward different parts of the earth.

A single antenna reflector can provide multiple beams by the use of feeds offset from the focal point. Separate reflectors, however, provide better efficiency and less crosstalk. Omnidirectional antennas serve a useful purpose for telemetry and command during the launch and orbital injection phases of the spacecraft's life, but once the spacecraft's altitude becomes stabilized correctly, these antennas generally serve only for back-up purposes.

4. Electrical Power Subsystem

The satellite generates power by using a solar array of silicon cells. In a spin--stabilized satellite the solar array consists of two concentric cylindrical panels of silicon cells. The forward panel is attached to the main structure and is divided into two arrays separated by a thermal radiator band. The aft panel is retracted over the forward panel during a transfer orbit and extended into its operating position in a geostationary orbit. In a transfer orbit, solar power is provided by the aft panel only. The disadvantage of a spin--stabilized satellite is that only one--third of the solar array is exposed to the sun at any time, resulting in power limitations. For a higher power level, a larger satellite is required to provide space for body--mounted solar cells. The three axis body--stabilized configuration can provide much more power by using deployed solar panels of wings. The array consists of many panels hinged together in two sets.

In a transfer orbit, the panels are folded and stowed by restraint bands against the north and south facing sides of the satellite. The outermost panel is partially illuminated by the sun and furnishes a small amount of solar power. When the satellite reaches the geostationary orbit, the array is deployed and full

power becomes available. In this operating position, the booms that fasten each set of panels to the satellite are normal to the plane of orbit, and it is only necessary to rotate the boom one revolution per day to keep the face of the array pointing toward the sun. Each array is driven by an independent but redundant motor. Because geostationary satellites experience 88 eclipses during 1 year on--station with a maximum duration of 70 min/day, batteries must be used to deliver power during an eclipse. Nickel--cadmium batteries are commonly used, but nickel--hydrogen batteries are replacing them because of the higher energy--to--weight ratio. The batteries are charged regularly by the solar array [Ref. 5].

5. Communication Frequencies

Frequencies for satellite communications are allocated internationally at World Administrative Radio Conferences (WARC) under the auspices of the International Telecommunications Union (ITU). Agreements reached in the international conferences after ratification by each participating country have the force of a treaty.

Characteristically, frequencies at the lower part of the spectrum are less susceptible to attenuation by rain and require less expensive

equipment than frequencies at the higher end of the spectrum. However, as the spectrum at the lower frequencies becomes saturated by an excessive number of users, higher frequencies become the only alternative.

Many systems utilize frequency reuse techniques in order to expand the available bandwidth. This is accomplished by employing orthogonal polarizations for channels operating in the same frequency band. Isolation of over 30 dB can be achieved by this method. Directional beams (spot beams) can also occupy the same frequency band by making use of spacial isolation.

Table II lists the frequency allocations for satellite communications, as well as other allocations and telemetry tracking and control (TT&C) [Ref. 6].

TABLE II

FREQUENCY ALLOCATIONS (In MHz)

Use	Downlinks	Uplinks
COMMUNICATION SATELLITES		
Commercial (C Band)	3,700- 4,200	5,925- 6,425
Military (X Band)	7,250- 7,750	7,900- 8,400
Commercial (K Band):		
Domestic	11,700-12,200	14,000-14,500
International	10,950-11,200	27,500-31,000
	11,450-11,700	
	17,700-21,200	
OTHER ALLOCATIONS		
Broadcast	2,500-2,535	2,655-2,690
Maritime (L-Band)	1,535-1,542.5	1,635-1,644
Aeronautical	1,543.5-1,558.5	1,645-1,660
TELEMETRY TRACKING AND COMMAND		
137.0-138.0, 401.0-402.0, 1,525-1,540		

E. MARITIME SATELLITE COMMUNICATIONS

1. Features of a maritime satellite communication system

A maritime satellite communication system consists of the space segment, shipboard earth stations, and land earth stations (coast earth stations). The space segment includes satellites and TT&C facilities for monitoring and controlling the satellite. The ship earth station is installed on board a ship, on floating facilities, or on a platform not permanently moored.

Figure 1.3 shows a general configuration of a maritime satellite communication system [Ref. 7].

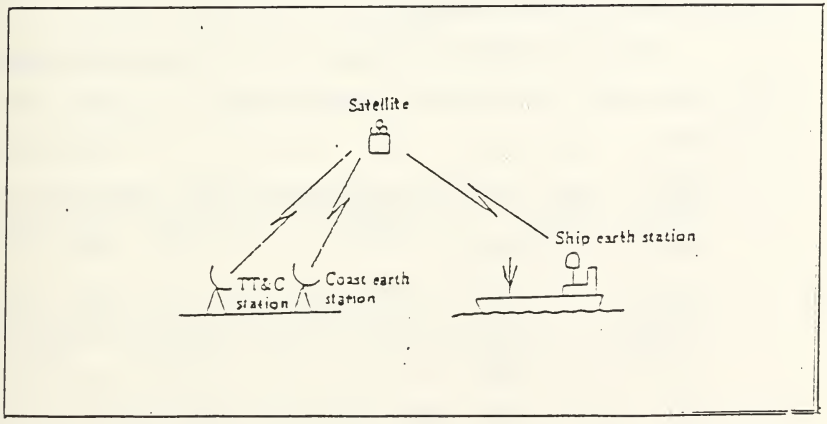

Figure 1.3 Configuration of maritime SATCOM system

According to a definition in the Radio Regulations, the link between a ship earth station and a satellite of the maritime satellite communication system belongs to the maritime mobile--satellite service, while the link between a coast or land earth station and a satellite belongs to the fixed--satellite service. Thus, maritime satellite communications can be regarded as a combination of these two services. Among the frequency bands allocated to the maritime mobile--satellite service, the 1.5 GHz and 1.6 GHz bands belonging to the so--called L--Band are used in practical communications for the present. For the link between a coast earth station and a satellite, frequency bands allocated to the fixed--satellite service are primarily used.

The noticeable features of the configuration of the maritime satellite communication system are as follows:

a. The L-Band involves considerably smaller free space loss and precipitation attenuation than the C-Band which is widely used in the fixed-satellite service.

b. Because of the limitations in the size of the antenna, the G/T of the ship earth station is remarkably small compared with that of the earth stations on land.

c. The effect of sea surface reflection of radio waves on communication quality cannot be neglected when the ship earth station is operated at a low elevation angle.

From the operational aspect, one of the major features is employment of a demand assignment system, in which a satellite link is established on a call--by--call basis by a coast earth station in response to a request from a ship earth station or terrestrial subscriber. This is mainly due to the sporadic traffic demands of ship earth stations characteristic of conventional maritime mobile service.

One of the particular features of ship earth station hardware (usually called ship terminals), is an antenna stabilization mechanism. This mechanism must be provided for directing the antenna toward the satellite under pitching and rolling conditions of the ship.

The fact that characteristics of the satellite link in the shore--to--ship direction differ from those of the link in the ship--to--shore direction makes it necessary to define an individual hypothetical reference circuit individually for each direction of the link. The CCIR (International Radio Consultative Committee) has defined two types of hypothetical reference circuits for telephony in the maritime satellite communication system. The first extends from coast earth station to ship earth station via space station (shore--to--ship), and the second extends from

ship earth station to coast earth station via space (ship--to--shore).

In these circuits, the interface of a telephone circuit is on the 4--wire voice grade interface point of both the coast earth station and the ship earth station, while associated devices such as echo suppressors are not included in the circuit. It should be noted, however, that if voice processing devices such as the compandor, coder, decoder, and the voice--activated carrier switch are used, they are included in the hypothetical reference circuit. A compandor consists of a compressor which compresses the volume range of the input voice signal at the modulator by a certain factor, and an expander which expands the output signal at the demodulator by the same factor.

2. Quality objectives of 50 Baud transmission

The quality objectives of 50 baud start--stop telegraph transmission are specified in Recommendation 552 of the CCIR as follows [Ref. 4]:

(1) Propagation conditions should not contribute any character errors for at least 95% of all calls with mobile terminals within the satellite service area; and (2) With the exception of blockage (the case where radio waves are screened by structures of a ship such as masts and communication quality

degrades) effects, propagation conditions should not contribute more than 8 errors in 100,000 characters with a 99% confidence level for mobile terminals at the edge of the service area.

As an example of a maritime satellite system, the feature of the INMARSAT System is taken up and its features are described in the following pages.

a. System configuration

The INMARSAT System consists of (1) the space segment (satellites and their TT&C stations), (2) ship earth stations which have access to the satellites, (3) coast earth stations which correspond with ship earth stations via satellites, (4) Network Coordination Stations (NCS) which conduct or assist the channel assignment to coast earth stations and ship earth stations, and (5) an Operations Control Center (OCC) which coordinates the operation of the overall system and maintains system information. All the satellites that compose the INMARSAT space segment have been leased from the organizations concerned.

In the INMARSAT System which includes two or more coast earth stations within each area of coverage, the so-called NCS scheme has been employed for coordination of channel assignment and other functions necessary for 4maintaining proper network

operations. The NCS services are being provided by the following coast earth stations:

Atlantic Ocean Region:Southbury (COMSAT,USA)

Indian Ocean Region:Yamaguchi (KDD,Japan)

Pacific Ocean Region:Ibaraki (KDD,Japan)

Figure 1.4 is a configuration of the INMARSAT System [Ref. 6].

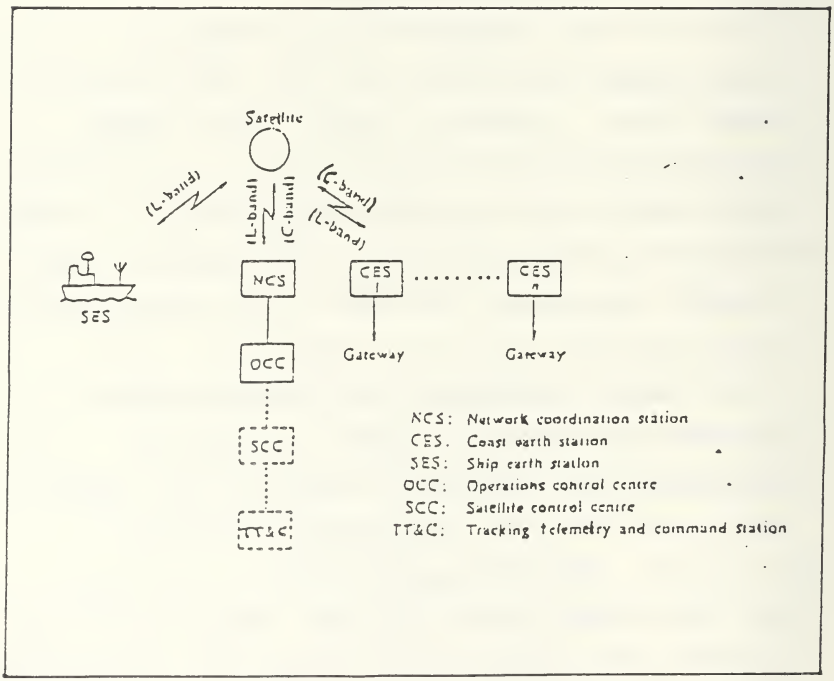

Figure 1.4 Configuration of INMARSAT system

b. Modulation and Access Scheme

The INMARSAT System has followed the modulation and access scheme of the MARISAT System. The fundamental channel types of the INMARSAT System are classified into four categories: telephony, telegraphy, request (ship--to--shore), and assignment (shore--to--ship). For telephony, the SCPC--FM (Single channel per carrier) system is used in both ship--to--shore and shore--to--ship directions, while for telegraphy, the PSK--TDMA system is used in the ship--to--shore direction and the TDM--PSK system in the shore--to--ship direction. For a request channel, the PSK-Random access system is used, while an assignment channel is set up by a TDM--PSK carrier which is also commonly used for telegraphy.

c. Link Power Budget and Frequency Planning

The channel capacity of satellites depends primarily on the satellite EIRP (Effective Isotropic Radiated Power) in the shore--to--ship direction.

The best tone S/N in the narrow band FM system is given by the following equation when C/No is above the threshold level:

$$\frac{S}{N} = \frac{C}{No} + 20 \log \frac{fp}{fm} - 10 \log fm + 10 \log \frac{3}{2}$$

Where C/No : Carrier power to noise power density ratio (dB-Hz),

fp : Test tone peak frequency deviation (Hz),

fm : Top frequency of a voice frequency band (Hz).

Although various types of demodulators are conceivable for the narrow band FM system, a threshold extension demodulator such as a PLL (Phase--locked loop) demodulator is actually used. This is because the satellite EIRP in the shore to ship direction is limited and system operation at around 50 dB--Hz (this corresponds to C/N = 5.5 dB when the noise bandwidth is 28 KHz) of C/No is required.

Since the frequency deviation for ordinary speech signals is considerably small as compared with the test tone peak frequency deviation, compandors are used in order to improve the S/N.

When a compandor is used, the proportionarity between the input and output signals can be maintained, since the voice signal compressed at the transmit end is expanded by the same factor at the receive end. Also link noise is reduced by the effects of the expander, resulting in a S/N that is much improved as a whole. The level of improvement of S/N is equal to the sum of speech signal and noise levels. When the speech signal level is sufficiently higher than the noise level, the S/N is improved by as much as

the difference between the signal level and the unaffected level. However, in actual circuits using compandors, sometimes there are favorable mental effects because the noise level is considerably reduced when the speech signal disappears. Sometimes there is subjective degradation in the speech quality due to the fact that a noise burst arises for a high level of expander input during the interval between disappearance of a speech burst and recovery of the expander performance. Therefore, it is important to subjectively assess the overall effect, taking into account these factors.

d. Ship Earth Station Equipment

(1) System Configuration. In order to provide an example of ship earth station equipment, the main features of a terminal which is used in the INMARSAT System are presented here.

The above deck equipment consists of the antenna, the antenna control system, power amplifier, low noise amplifier, etc. These are installed in a hard radome in order to protect them against wind, waves, rain, snow, etc.

The ship earth station equipment consists of what is installed above and below the deck as shown in Figure 1.5 [Ref. 6].

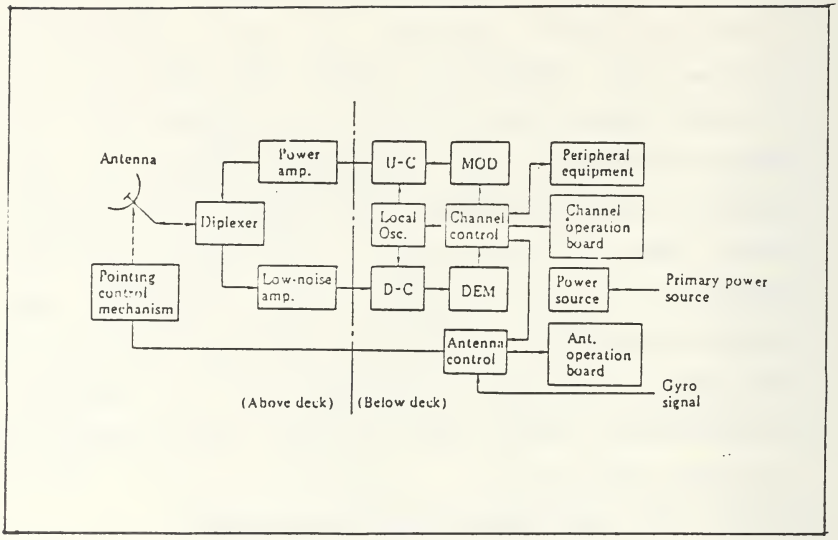

Figure 1.5 Above and below deck equipments

The equipment installed below the deck consists of frequency converters, a modulator and demodulator, channel control unit, antenna control unit, operating board, and peripheral equipment. The primary power and the gyrocompass output are provided by the ship. Signal transmission between the above deck and below deck equipment is made at L-Band frequencies.

Since ship terminals are operated in a maritime environment, they are required to withstand rather severe environmental conditions.

(2) Antenna

(a) Attitude Stabilization. Since the half power beamwidth of a parabolic antenna of 1.2 m diameter is about 10 degrees in the 1.5 GHz band, antenna attitude stabilization is required for maintaining normal performance of the terminal against ship's motions, e.g. rolling of $\pm 30^{\circ}$ and pitching of $\pm 10^{\circ}$.

Possible antenna mount methods are conceivable utilizing 2--axis, 3--axis, and 4--axis systems corresponding to the number of axes of antenna rotation. The 2--axis system has difficulties in driving the axes against roll or pitch of the ship when the antenna is pointed to the zenith, the bow, or the stern of the ship with a low elevation angle. In the case of the 3--axis system, these defects are removed. However, this system must have the rather complex capability to coordinate transformation, as in the case of the 2--axis system, because it must always provide the information indicating an angle to the direction of the satellite against ship motions such as roll and pitch. In the case of the 4--axis system a horizontal plane is always maintained against ship's motions by

controlling the X and Y axes. The direction to the satellite is secured by controlling the azimuth--elevation axes mounted on this horizontal plane.

For stabilization of the antenna attitude, there are two basic methods; electrical and mechanical. In the case of the electrical method, which is most widely used, ship motions are detected as a torque variation by gyroscopes or chemical sensors, and adjustment is made by a servo mechanism.

The mechanical method involves two different approaches; one uses fly--wheels and the other a pendulum. The former needs no electrical arrangement such as a servo system, but the system is likely to become bigger in size and weight than the electrical method. The latter is more simple in structure, but it is not suited to high gain antennas with a relatively narrow beam width because high accuracy cannot be achieved in the antenna attitude stabilization.

(b) Tracking the satellite. With the 4--axis stabilization system, the required information for tracking a satellite is the azimuth and elevation angles of the satellite since the antenna is mounted on a horizontally stabilized plane. Such information can be obtained by calculation if the positions of the satellite and ship are accurately known. Manual control

is feasible, however, in normal operation automatic tracking is practiced. The antenna control signals for azimuth and elevation are supplied from the auto--tracking system, supplemented by the gyrocompass output for azimuth control.

As a method for auto--tracking, the following three systems are conceivable; (1) step track system, (2) mono--pulse system, and (3) conical scan system.

For a parabolic antenna with a diameter of 85 cm to 1.2 m, extremely high tracking accuracy is not necessary. Thus the step track system is usually used from the viewpoint of simplicity of the structure.

(3) Transmit and receive amplifiers. In the existing maritime satellite communication systems, an EIRP of about 37 dBW is required for a ship terminal. When a parabolic antenna of 1.2 m diameter is used, the required output power of a transmit amplifier is 15.3 dBW (approximately 34 W), assuming that the antenna gain is 23.9 dBi, random loss 0.2 dB, feed loss 1 dB (cable length 5 m) and the antenna gain decrease due to tracking errors is 1 dB. Since the output of such a level can only be obtained by using a Class--C transistor amplifier, multiple carriers cannot be amplified simultaneously.

As the receive amplifier, a Low Noise Amplifier (LNA) with a Noise Figure (NF) of about 2.5 dB is required to achieve a G/T of -4 dBK with an antenna of 1.2 m diameter; while an amplifier with an NF of about 1 dB is required for an antenna of 85 cm diameter [Ref. 8].

The recommended environmental conditions for ship earth stations in the INMARSAT system are [Ref. 8]:

Ambient temperature	
Above-deck	-35 - +55
Below-deck	0 - +45
Relative humidity	Up to 95% at 40C
Spray	Solid droplets from any direction
Icing	Up to 2.5 cm of ice
Precipitation	Up to 10 cm/hour
Wind	Normal operation with relative average wind up to 100 knots
Prime power variations	
Frequency	+ 6%
Voltage	+ 10%

Viabration	Frequency range(Hz)	Peak amplitude(mm)
Above deck	4-10	2.54
	10-15	0.76
	15-25	0.40
	25-33	0.23
Below deck	4-15	0.76
	15-25	0.40
	25-33	0.23
	33-40	0.13
	40-50	0.07
Antenna motions		
Roll	+30(period 8s)	
Pitch	+10 (period 6s)	
Yaw	+8 (period 50s)	
Surge	+0.2g	
Sway	+0.2g	
Heavy	+0.5g	
Turning rate	6/s	
Headway	30 Knots	

F. PRACTICAL PROBLEMS OF SATELLITE COMMUNICATIONS

This section of the thesis discusses and describes briefly some of the major problems encountered by a communication satellite.

1. Link calculations

a. Antenna Gain

Gain is perhaps the key performance parameter of an earth station antenna because it directly affects the uplink and downlink carrier power. For an antenna, the gain is given by the formula:

$$G = \eta \frac{\pi 4A}{\lambda^2} = \frac{\pi 4Af^2}{c^2}$$

For a circular aperture it follows that

$$A = \pi D^2/4$$

Therefore $G = \pi f D^2/c$

Where

A = Antenna aperture area $(m)^2$

f = Radiation frequency (Hz)

c = Speed of light = 2.9979×10^8 m/s

η = Antenna aperture efficiency < 1

D = Antenna diameter (m)

λ = Radiation wavelength (m)

b. Basic Link Analysis

A basic link analysis is shown in Figure 1.6.

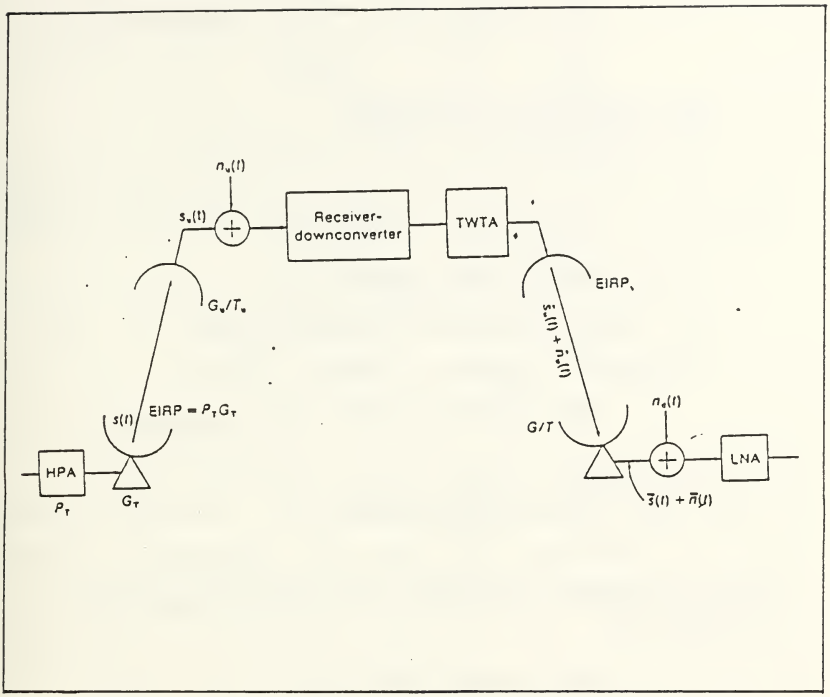

Figure 1.6 Basic link analysis

The communication links are of three general types:

1. Point--to--point links in which a great many communications are funneled to a central point and carried over a single trunk line to another central point from which they fan out to their destinations.

2. Point--to--mobile links between a central communication center and a moving target such as a ship or an aircraft.

3. Mobile--to--mobile links such as between the individual aircraft or ships.

The uplink free space loss is given by

$$Lu = \left(\frac{4d_u\pi}{u}\right)^2 = \left(\frac{4f_u du\pi}{c}\right)^2$$

Where d_u = Uplink slant range (m)

λ_u = Uplink wave length (m)

f_u = Uplink carrier frequency (Hz)

c= Speed of light = 2.9888 x 10^8 m/s

The uplink carrier power

$$Cu = \frac{EIRP}{L}\left(\frac{c}{4f_u d_u \pi}\right)^2 Gu$$

Where L=Antenna tracking loss and atmospheric attenuation.

The uplink noise power

$N_u = k\ T_u\ B$ Where

T_u : Satellite system noise temperature (K) (Which is about 290K since the antenna always sees a hot earth)

B : Noise bandwidth of satellite channel (Hz)

k : Boltzmann's constant = 1.38 x 10^{-23} J/K

So the uplink carrier-to noise ratio is:

$$\left(\frac{C}{N}\right)_u = \frac{EIRP}{L}\left(\frac{c}{\pi 4 f_u d_u}\right)^2 \left(\frac{G_u}{T_u}\right)\left(\frac{1}{kB}\right)$$

In the same way we can calculate the downlink carrier--to--noise ratio $(C/N)_d$ and the link carrier--to--noise ratio is:

$$\frac{C}{N} = \left[\left(\frac{C}{N}\right)_u^{-1} \left(\frac{C}{N}\right)_d^{-1}\right]^{-1}$$

2. Launching

The launching of a satellite is a difficult and expensive matter. Experience has shown that new or modified launching vehicles are uncertain in their operation, and even vehicles which have been used many times before are prone to failure.

This fact together with the high cost of launchings and higher cost of developing a new vehicle, leads one to the conclusion that the only economically practical way to launch a satellite is to use the best adapted, well tried,currently available vehicle.

3. Tracking

Tracking is another problem. It has frequently been argued that the fact that a stationary satellite need not be tracked leads to a substantial economic

advantage. It has been proposed that stationary, non-steerable antennas might be used.

4. Cosmic radiation and other space-induced problems

The earliest satellites used stored power, so their power level was low and their life short. They were soon followed by solar power absorbers, still of low power, but with much longer life, and in a few cases, apparently indefinite life.

In current satellites, the amount of power has increased appreciably. Most of this added power has resulted from increasing the size of the solar absorbers. This trend is expected to continue and in addition, new power sources including nuclear reactors are planned.

Most satellites depend on solar cells together with storage batteries for electrical power. Sunlight has an energy of about 130 W per square foot and solar cells can turn about 10% or 13 W of this into electric power initially.

While the solid state electronic devices are also subject to the hazards of cosmic radiation, the transistors and diodes are in general less sensitive to the radiation than are solar cells. Furthermore, they are better protected, both by metal encapsulations and

by their location within a metal--clad satellite structure.

This does not mean however, that satellite electronic equipment other than solar cells does not face special problems and hazards in space. Vacuum and gas at atmospheric pressure are good insulators but during ascent, reduced pressures are encountered in which a discharge can be initiated at a comparatively low voltage. Once in orbit pressurized containers may leak. The seals of storage batteries sometimes leak as well. Vapors from apparatus can produce appreciable gas pressures in enclosed spaces even if these are not completely gas tight.

Ultimately, only thermal radiation cooling is available. Heat must conduct to radiating surfaces. There can be convection, even in a pressurized container, only if the satellite is spun, because there is no weight in an orbiting satellite. In an alternate environment of sunlight and shadow, the temperature variation of the exposed parts of a satellite will be large, though the thermal capacity of interior parts can reduce their temperature fluctuation.

5. Design problems in equipment

The required power affects the life profoundly. Life tests show that 5 W travelling wave tubes have not

failed after four years, and it is believed that carefully designed 2 W tubes, which would be sufficient for carefully designed satellite communication systems, would have an assured life of 10 years or more. On the other hand, it is beyond the current state of the art to make long life tubes for hundreds of watts, and even tens of watts pose serious, unsolved problems.

Another power related consideration is satellite weight. Higher power means more weight is added to the satellite. Lower power makes it possible to launch more satellites with a given vehicle. The one advantage of low power is that it tends to reduce interference. Also we have to remember that the required power depends on the method of modulation which is used.

Using FDMA and SSMA we can get a percentage of satellite output power (efficiency) of the order of 80%; whereas in the case of TDMA, power lost to intermodulation products does not arise. Therefore, power utilization in the case of TDMA is approximately 80 to 95% [Ref. 2].

Bandwidth is a major problem in equipment design. The percentage of bandwidth which can be utilized for information transmission in a system depends on the number of accesses, the type of message modulation, and the required reception quality. It has

been proved practically that TDMA makes the most efficient use of bandwidth.

Yet another practical problem is the possibility of interference between satellite system and ground microwave systems,which is an extremely important matter. Several general principles are clear. One of these is that anything that allows reduced RF power in a satellite system minimizes interference with ground systems.

6. Frequency dependent attenuation

There are a number of frequency dependent effects on propagation that increase the total transmission loss above the space loss of the satellite--earth terminal path. These propagation losses are discussed in the following paragraphs.

a. Propagation effects

UHF satellite communications are subject to two propagation phenomena whose effects are manifest in received signal strength variations: Multipath and ionospheric scintillation. While the physical mechanisms in both cases are complex and difficult to precisely characterize, there are simple models which predict results in reasonable agreement with actual observations. Moreover, extensive experimentation and measurement programs have been undertaken using both

experimental and operational UHF satellites to determine the effects of these two mechanisms.

(1) Multipath. The multipath effect is modeled as one of slow, frequency--flat fading, generally to depths of 5 dB but with occasional deeper fading.

Some of the characteristics are:

a. Significant fading occurs only at low elevation angles (Up to 5 for shipboard terminals).

b. Typical fade depths over water are 4--5 dB, with less severe fading observed over land.

c. To provide protection against multipath fading by frequency diversity requires a frequency separation on order of 100 KHz for aircraft links, and much greater separation in the shipboard case. This implies that over the relatively narrow bandwidths of interest (up to 25 KHz) the fading can be considered frequency--flat.

(2) Ionospheric scintillation. Ionospheric scintillation is another attenuation effect, and it is primarily important at frequencies below 1 GHz. However, even at microwave frequencies above 1 GHz, it is still significant.

> "----Ionospheric scintillation is caused by irregularities in the night time, F layer ranging from 200 to 600 Km in altitude. The irregularities appear to be elongated regions with the longer axis parallel to the earth's magnetic field lines. Axial ratios greater than 60 to 1 have been measured. The effect of these irregularities is alternatively to produce signal enhancement and negative fades. The refractive index of the ionosphere is a function of radio frequency, and irregularities in the ionosphere have progressively less effect as the frequency increase." [Ref. 28]

Scintillation is confined to zones near the geomagnetic poles and geomagnetic equator. It generally occurs at night and is a function, to some extent, of the season of the year and of the sunspot cycle.

b. Atmospheric Loss / Attenuation

The atmospheric loss or attenuation (La) can be calculated from existing data and is given by:

$$La(dB) = \frac{L_a(dB) + b_p(p_o - 7.5g/m^3) + c_T(21C - T_o)}{\sin E}$$

Where L_a = Zenith one--way attenuation for moderately humid atmosphere ($7.5g/m^3$ surface water) and a surface temperature of 21°C;

b_p = Water vapor density correction coefficient;

c_T = Temperature correction coefficient;

p_o = Surface water vapor density (g/m^3).

c. Rain-induced Attenuation

Besides the ever--present free space loss and the atmospheric absorption which is significant only in bands centered at frequencies of 22.5 GHz (Water vapor), 60 GHz and 118.8 GHz (oxygen), satellite communications above 10GHz must deal with another type of attenuation caused by rain. Although rain is not a problem in the 6/4--GHz band, it is a major concern that strongly influences link design as satellite

communications move into 14/12 and 30/20 GHz bands to avoid orbital congestion.

Besides causing attenuation that directly reduces the signal power, rain also increases the sky noise temperature significantly. Since the antenna noise temperature is a function of the sky noise temperature, rain in effect increases the system noise temperature of the earth station.

The noise power available over a bandwidth B is simply kT_rB. The noise power after passing through rain is:

$$kT_rB \; / \; L_r$$

where T_r = rain temperature and L_r = rain attenuation.

The increase in noise temperature (DT) is:

$$DT = T_r \; (1 - 1/L_r)$$

In practice the T_r is usually taken to be 273° K.

The increase in noise temperature due to rain is added directly to the earth station system temperature and further reduces the downlink carrier--to--noise ratio. The increase in noise temperature due to rain does not effect the system noise temperature of the satellite because its antenna always looks at a hot earth at 290°K.

G. RELIABILITY OF SATELLITE COMMUNICATIONS SYSTEMS

1. Introduction

Reliability is the probability that the system will perform satisfactorily over its specific life. It depends on the two principal components of the system, the satellite and the ground segment.

Availability is the probability that the system is operating satisfactorily at any point in time. Availability moreover depends on the success of the launch, replacement time, number of operational satellites and back-up satellites (in orbit and on the ground).

For earth stations, availability does not solely depend on reliability but also on the maintainability. For a satellite, the availability depends only on its reliability, as no maintenance is possible.

2. Failure rate

A complex piece of equipment such as a satellite, displays two modes of failure:

Accidental failure (random failures), and failure caused by wearing out (bearings, solenoid--operated valves, TWT cathodes) or exhaustion of expendables.

Assuming instantaneous replacement of a failing part, it is possible to determine the instantaneous failure rate for a given piece equipment over its life.

In a satellite the infant mortalities are eliminated in advance of the launch by various methods such as heat cycling and operation of the equipment and components. Therefore over the duration of the mission, most equipments comprising electronic and mechanical components will exhibit a constant failure rate λ often expressed in Fit (number of failure per 10^9 Hours).

3. Probability of survival or Reliability

If an equipment has a failure rate of λ the reliability (R) at an instant t is given by:

$$R = e^{-\lambda t}$$

4. Mean Time To Failure (MTTF)

This is the mean value of the time (T) to first failure and can be used to predict life of the equipment. For the case with a λ constant, this reduces to:

$$T = 1 / \lambda$$

In the case of a satellite with a maximum mission life U, the average life τ is given by:

$$\tau = T \left(1 - e^{-U/T} \right)$$

and τ is dependent on the mean time to failure T, as defined for a constant failure rate λ.

τ/T is the probability of failure during the mission life U.

5. Mission reliability

To ensure a service defined by a given availability A during a fixed period L, one must plan the number of satellites to be launched during the system lifetime L. This is of major importance in the average cost of service.

The required number of satellites and the system availability A will be evaluated in the following two typical cases, in which the time required to replace a satellite in orbit is T_R and the probability of success of the launch is p.

Case I. No spare satellite in orbit

Required number of satellites: Since the average life of a satellite is τ, during L years, on average $S = L / \tau$ satellites have to be placed in orbit. As the probability of success of each launching is p, $n = S/p$ launchings must be attempted so:

$$n = \frac{L}{pT(1-e^{-U/T})}$$

System availability: Satellites which are near the end of their life U must be replaced sufficiently early so that even in case of a launch failure another launching can be completed in time. The unavailability of the system in this instance is low compared with the unavailability due to accidental failures.

During the life U, the probability of a satellite random failure is $P_f = 1 - e^{-U/T}$. In L years, S replacements have to be made of which $P_f \times S$ for accidental failure. Each replacement requires a time T_R if successful and, on average, a time T_R / p. The average duration of unavailability during L years is:

$$\frac{P_f \times S \times T_R}{p} = \frac{L \times T_R}{p \times T}$$

Hence the system unavailability is:

$$B = \frac{T_R}{p\ T}$$

and the system availability $A = 1 - B$ is:

$$A = 1 - \frac{T_R}{p\ T}$$

Case II. Back--up Satellite (in orbit space) available.

Taking the prudent, though pessimistic view that a back--up satellite has a failure rate μ and a life U equal to an active satellite, it would be necessary during a year to launch twice as many satellites as in the preceding case:

$$\mu = \frac{2L}{p\ T\ (1-e^{-U/T})}$$

But in this case, taking into account that TR/T is small the availability of the systems becomes:

$$A = 1 - \frac{2T_R^2}{p^2\ T^2}$$

H. MULTIPLE ACCESS

1. Frequency Division Multiple Access (FDMA)

The simplest and most widely used multiple access technique of satellite communications is Frequency Division Multiple Access (FDMA) where each earth station in a satellite network transmits one or more carriers at different center frequencies to the satellite transponder. Each carrier is assigned a

frequency band with a small guard band to avoid overlapping between adjacent carriers. The satellite transponder receives all the carriers in its bandwidth, amplifies them, and retransmits them back to earth. The earth station in the satellite beam served by the transponder can select the carrier that contains messages intended for it. In this type of system each carrier can employ either analog modulation, such frequency modulation (FM) or digital modulation such as phase shift keying (PSK). A major problem in the operation of FDMA satellite systems is the presence of intermodulation products in the carrier bandwidth generated by the amplification of multiple carriers by a common TWTA in the satellite transponder that exhibits both amplitude nonlinearity and phase nonlinearity. As the number of carriers increases, it becomes necessary to operate the TWTA close to saturation in order to supply the required power per carrier to reduce the effect of downlink thermal noise.

There are two main FDMA techniques in operation today.

a. Multichannel--per--carrier transmission (FDM--FM--FDMA), where the transmitting earth station frequency division multiplexes several singal sideband suppressed carrier telephone channels into one carrier baseband assembly which frequency modulates a RF carrier and is transmitted to a FDMA satellite transponder.

b. Single Channel Per Carrier (SCPC) transmission,where each telephone channel independently modulates a separate RF carrier and is transmitted to a FDMA satellite transponder. The modulation can be analog, such as FM, or digital such as PSK [Ref. 2].

The advantages and disadvantages of FDMA are summarized as follows [Ref. 10]:

A FDMA frame structure is shown in Figure 1.7

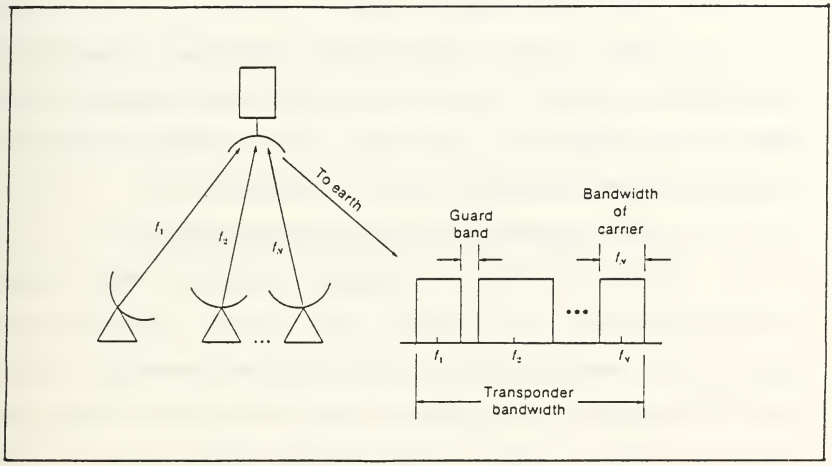

Figure 1.7 FDMA frame structure

a. Advantages

1. No special circuitry or equipment is required.
2. No network timing is required.
3. Voice can be transmitted in normal analog form.

b. Disadvantages

1. The system is vulnerable to jamming.
2. Intermodulation products waste power and add noise to the signal.
3. Operating frequencies must be carefully selected to reduce interference from intermodulation product signals.
4. Uplink power coordination is required to achieve efficient use of transponder power and to avoid large-signal capture.

FDMA is the technique presently used in the INTELSAT, IDCSP (Initial Defense Communications Satellite Program), and the DSCS (Defense Satellite Communications System) phase II satellites.

2. Time Division Multiple Access (TDMA)

Time Division Multiple Access is a multiple access protocol in which many earth stations in a satellite communications network use a single carrier for transmission via each satellite transponder on a time division basis. All earth stations operating on the transponder are allowed to transmit traffic bursts during a periodic time frame the TDMA frame. Over the length of the burst, each earth station has the entire transponder bandwidth available to it for transmission.

The transmit timing of the burst is carefully synchronized so that all the bursts arriving at the satellite transponder from a community of earth stations in the network are closely spaced in time but

do not overlap. The satellite transponder receives one burst at a time, amplifies it, and retransmits it back to earth. Thus every earth station in the satellite beam served by the transponder can receive the entire burst stream and extract the bursts intended for it.

In a TDMA network, each earth station periodically transmits one or more bursts to the satellite. The input signal to the satellite transponder carrying TDMA traffic thus consists of a set of bursts originating from a number of earth stations. This set of bursts is referred to as a TDMA frame. It consists of two reference bursts RB1 and RB2, traffic bursts,and the guard time between bursts. Each TDMA frame normally consist of two RB for reliability.

Theoretically, TDMA appears to be the most efficient multiple access technique. TDMA can provide the highest information rate for a given repeater output power.

The advantages and disadvantages for TDMA are summarized as follows [Ref. 10]:

a. Advantages

1. It is a very efficient system in terms of information capacity.
2. There is no interaction between signals, therefore, intermodulation is not a problem.

3. There is no problem of large-signal capture of the satellite; hence, earth station power coordination is not required.

4. It can accommodate earth stations of different sizes and of widely different characteristics.

5. It can accommodate earth stations having widely varying channel requirements.

b. Disadvantages

1. Network time is required.

2. All information must be converted to digital form.

3. The system is vulnerable to selective jamming.

4. Buffering of data is required in the TDMA modem.

A TDMA frame structure is shown in Figure 1.8

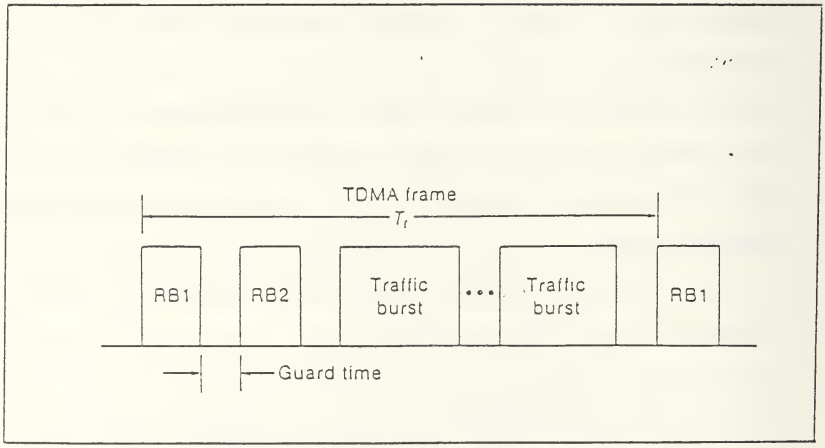

Figure 1.8 TDMA frame structure

3. Spread Spectrum Multiple Access (SSMA)

With SSMA each carrier signal simultaneously occupies the same wide portion of the spectrum. The bandwidth of the signal will usually be at least 10 MHz wide and may occupy the whole bandpass of the satellite.

SSMA is usually accomplished by adding the digitized voice signal, or other digital signal, to a high rate pseudo-random noise code formed by a shift register generator. The advantages and disadvantages of SSMA may be summarized as follows [Ref. 10]:

a. Advantages

1. It automatically provides the system with a high degree of jamming resistance at low data rates.
2. A passive monitor can not tell how much traffic is being passed over the system, since the pseudo-random noise code looks the same regardless of whether or not it is carrying intelligence.

b. Disadvantages

1. The spread spectrum modulation and demodulation equipment adds cost and complexity to the system.
2. Wideband amplifiers are required increasing cost and power requirements.
3. Each earth terminal pair must keep their pseudo-random noise generators synchronized while communicating with each other.
4. All information must be converted to digital form.

II. FLEET SATELLITE COMMUNICATIONS

A. MILITARY SATELLITE COMMUNICATIONS

Satellite communication systems offer a unique transmission medium which can be exploited for a number of diverse military applications. In a number of cases, the medium can provide vastly improved reliability and capacity compared to high frequency (HF) transmission via ionospheric reflection or scatter. Also vulnerability to circuit disruption at intermediate relay points is minimized. Because the potential of this new medium has become more widely recognized, the demand for satellite service is increasing rapidly in the DoD community. On the other hand, satellite communication systems are costly, and the portions of the radio frequency (RF) spectrum allocated for their use are limited and crowded.

The system presently serving the military long--distance trunk requirements and providing limited contingency and mobile service is known as the Defense Satellite Communications System (DSCS). This is a strategic point--to--point system. Its primary mission is to support the Worldwide Military Command and Control System (WWMCCS). The requirements that the military have posed for an operational system are the following:

1. Positive operational control: The system must be under military command and control at all times without dependence on foreign companies or governments.

2. Mobility and remote area access: Military communications cannot be limited to fixed stations and points of high density traffic. A commercial system can employ large, elaborate ground stations to handle the traffic burden of populous areas, but a military system must be able to penetrate remote and sparsely populated areas as emergencies dictate.

3. Protection against physical attack (invulnerability): A military system demands special protective measures both for the ground stations and the satellite repeaters. Hardening, dispersal and mobility are protective factors for ground stations; the space repeater system should be designed to operate even if some of the repeaters are destroyed by hostile action.

4. Protection against electronic countermeasures: Even in peacetime, a military system must be able to overcome jamming action. This requires the ability to switch from one frequency to another and entails a much larger ratio of radio frequency bandwidth to information bandwidth than would be normally used in a commercial system. Different modulation techniques and

higher transmitter powers also may be required to protect against jamming.

5. Low capacity and classified message transmission (security): A military system requires relatively low capacity for a few voice, teletype or digital data channels. However redundant or multiple channels are important in case of countermeasures. Also cryptographic security requires bandwidth and transmission features not normally required of commercial systems.

6. Separate frequencies for military use: The choice of frequencies for use in satellite communications poses difficult problems. The military now have bands of frequencies assigned for its own use in each country. They also intend to take full advantage of the special bands set aside in the Geneva radio revisions for satellite communication services. International agreement on the use of civilian bands now shared among diverse types of users for military satellite communication purposes might be difficult or impossible under a commercial satellite system encompassing military requirements.

7. Reliability: In order for a military communication system to fulfill its purpose it must be always available. The availability of a system depends on several interlocking factors; the reliability of the

equipment and components employed; the reliability of the particular communication media employed; and the skill and knowledge of the personnel operating and maintaining the system. The requirements for reliability are much more stringent for a military system, for even a brief failure of the military system might have disastrous political and international consequences. The military system is often forced to provide this reliability while operating in a much more difficult environment than would ever be selected for a commercial system.

8. Capacity: The military services require more and more communications channels. This increase in requirements is especially true of the channels capable of handling digital traffic.

9. Quality: The quality of the transmission required in the military system differs from commercial practice. While the military may relax quality requirements for tactical circuits, the strategic long haul circuits are comparable to those in commercial systems.

10. Military frequency bands: Three frequency bands are mainly used for military satellite communication systems. UHF (225 to 400 MHz), SHF (8/7 GHz), EHF (40/20 GHz). In first approximation, by clear sky condition, the available down link carrier-

-to--noise density (C/N_o) over a specific coverage area is not frequency dependent for a given RF power amplifier on board the dependent for a given RF power amplifier on board the satellite, low noise receiver, and antenna size at the terminal user.

However, for the same antenna size at the terminal user, the directivity of the antenna increases with the frequency. Also the terminal becomes less polluting in the orbit direction, and more difficult to jam on the down-link, but also more difficult to point if it is used on a higher frequencies. The allocated bandwidth also increases with the frequency, giving more capacity to a no power limited down--link. Larger bandwidth is also very useful to increase the protection in a military system.

B. TACTICAL SATELLITE DEVELOPMENT

A second development and of more interest to the Navy, is the tactical satellite system designed to effect connectivity between mobile sea platforms and operational commanders ashore. Whereas strategic communications rely on large fixed antennas sites, tactical satellites were designed for the complementary function of operating with small shipboard, airborne, and land--mobile terminals. The main strategic and tactical communication systems are:

1. LES 1--6 (Lincoln Experimental Satellites)

This is a strategic communication system and was designed to provide satellite communications between mobile tactical terminals including aircraft and ships at sea. Strategic satellite communications typically use frequencies between 7.5 and 8.5 GHz, and within these frequencies a directional antenna is required.

The Lincoln Laboratory constructed 6 satellites (LES 1--6) which were used to investigate various aspects of tactical communications.

The LES objectives were to demonstrate:

a. Communications with small terminals

b. High efficiency, solid state transmitters

c. Electronically despun antennas

d. Techniques for station keeping and altitude control.

The first three satellites used standard SHF (X--band) frequencies that were tested successfully on SYNCOM. The power was 200 mw. The eight horns, providing omni--directional coverage, were linked to sensors that determined the direction of the earth and spin rate of the spacecraft.

LES--4 had some improvements in components which resulted in significantly lower receiver noise while increasing effective isotropic radiated power

(EIRP) at the transmitter to 3 dBw. There was a gain of 9 dB over LES 1--3 [Ref. 11].

EIRP is the power radiated from an earth terminal or satellite transponder and is found by the formula:

$$EIRP = Pt \times Gt$$

$$EIRP\ (dBw) = Pt\ (dBw) + Gt\ (dBw) - L\ (dB)$$

where Pt = Transmitter power

Gt = Transmitter antenna gain

L = Loss of waveguide

LES 5--6. By mid--1967, the Lincoln Laboratory had determined theoretically that a satellite transmitting in the military UHF band (225 to 400 MHz) would reduce the shipboard antenna problems that were encountered at SHF. These problems at SHF generally arose from the highly directional nature of the receiving antenna system. The greater energy capture of simple UHF antennas was a favorable factor.

In July 1967, LES--5, was launched successfully into near-synchronous orbit (18,100 nautical miles altitude). LES--6 launched in September 1968, was very similar to LES--5, but was placed in a geosynchronous orbit above the equator. Each had a single transponder with a 100 KHz or 300 KHz (LES--5)/500 KHz (LES--6) signal bandwidth. The trend of increasing EIRP remained true for these satellites. LES--5 developed

30 watts of transmitter power with a 16.5 dBw EIRP; LES--6 developed a peak of 120 watts with 29 dBw EIRP.

2. Tactical Satellites (TACSAT)

This program was designed to provide satellite communications between mobile tactical terminals including aircraft and ships at sea.

TACSAT's design requirements dictated a number of features not present in previous communication satellites. Since there was virtually no interest in tactical communications in the commercial field, engineers who worked on TACSAT were frequently treading on new ground. Almost a kilowatt of prime power was required for the high power transmitters, which dictated a very large 1600 pound cylindrical body to provide the requisite solar panel area. TACSAT was spin stabilized. However, because of large antenna structure and launch vehicle fairing constraints, it did not spin about the axis having the maximum amount of inertia. This potentially unstable condition was controlled by special stabilizing elements. The communication subsystem consisted of both an SHF (X--Band) and UHF frequency band repeater capable of operation with selectable bandwidths from 50 KHz to 10 MHz. To allow flexibility for user terminals, a crossover mode of operation was designed into the

system. The crossover mode permitted a UHF uplink to SHF downlink or inversely.

A satellite control earth terminal transmitted tracking, telemetry and control (TT&C) signals which commanded TACSAT to utilize a specific crossover mode if required. The satellite itself generated UHF and SHF beacon signals which were used as references for all transmit and receive function frequencies generated at the mobile terminals. A FDMA scheme was used and in order to eliminate the interference between users there was a guard band between carrier frequencies. A total of 230 watts of output power was available out of the combiner, yielding from 29.3 dB to 16.7 dB of ground terminal receiver carrier--to--noise ratio. The higher value was for the strongest UHF terminal, the lower value was for the weakest terminal. TACSAT was an unqualified success. It demonstrated, under operational conditions, the Navy's ability to transfer data and voice traffic from shore stations to ships at sea via a satellite link.

A truly operational system was now reusable using TACSAT type satellites, however funding limitations and production problems forced a four year delay in the deployment of such a system.

C. OPERATIONAL SATELLITE SYSTEM

The Navy UHF satellite communication system provides communication links via satellites between designated mobile units and shore stations. The area of coverage for these communication links is worldwide between 70 degrees North and 70 degrees South.

Three satellite constellations are currently in operational use. These satellites are called GAPFILLER, FLTSATCOM, and LEASAT. The system includes satellites, RF terminals, subscriber subsystems, personnel, training, documentation, and logistic support. Although any part of the system may operate as a separate entity, the system integration provides connection for message traffic and voice communications for DoD long haul communication networks. Inherent in the system architecture is a backup capability between shore stations in the event of an outage. This backup capability is constrained to selected subsystems and the ability of shore stations to access various satellites.

The Navy UHF SATCOM system represents a composite of information exchange subsystems that use the satellites as a relay for communications. Each subsystem has been structured to address a selected area of Naval communications.

1. GAPFILLER Satellite

The GAPFILLER satellite called GAPSAT had two important characteristics that allowed for a rapid employment of the system. The first characteristic was that it would be leased from a commercial satellite common carrier, and secondly, it would utilize existing space--segment communication technology. Primarily GAPSAT was able to provide needed service for approximately two years before FLTSATCOM was ready for service.

Three GAPSAT spacecraft were launched into equatorial orbit in 1976--1977. They were positioned over the Atlantic, Pacific, and Indian Oceans at 15° W, 176.5° E and 73° E respectively. Each covered approximately 60 million square miles, or roughly one-third of the earth's surface with some overlap.

The Navy leased portion of GAPSAT consisted of a receiver, channel power amplifiers, and a multiplexer. The receiver translated the received carriers to intermediate frequencies (IF) in the 20 MHz range then separated them into one 500 KHz wideband channel and two 25 KHz narrowband channels. The wideband channel provided a number of accesses with a combined power output of 630 watts. Because Frequency Division Multiple Access (FDMA) was the multiple access technique for the wideband channel, both frequency

separation and uplink power control monitoring were essential to control intermodulation products which caused signal interference. The narrowband channel, though hard limited, supported a single uplink signal, namely the Fleet Broadcast. This broadcast was transmitted uplink from a shore communication facility, retransmitted by GAPSAT after translation to the appropriate down--link frequency and received by all ships in the satellite footprint. The channel capacity for the Fleet Broadcast was a composite of 1200 bits per second (bps) multiplexed using 15 data bits per frame (plus one synchronization pulse). This time division multiplexing scheme using phase shift keying (TDM--PSK) allowed the Fleet Broadcast to support 15 separate 75 bps traffic circuits [Ref. 10].

Other characteristics are:

EIRP Wideband channel	28 dBw
EIRP Narrowband channels	23 dBw
Receive G/T	-18 dB/K
UHF Antenna coverage	19 (Earth coverage)

AN/WSC--5 and AN/WSC--3 transceivers provide the UHF radio path (uplink-downlink) both ashore and afloat.

The AN/WSC--3 is designed for single channel, half duplex operation, whereas the shipboard AN/WSC--5 is designed for one full duplex and two half duplex

channels. During the GAPFILLER period two multichannel broadcasts were provided, in an active status, to support the transmission of messages from shore to surface ships. Each broadcast provided 15 traffic channels. Two information exchange systems, the Common User Digital Information Exchange Subsystem (CUDIXS) and the Submarine Satellite Information Exchange Subsystem (SSIXS) commenced operation during the GAPSAT time frame.

2. Fleet Broadcast Receivers

In concert with the leasing of GAPSAT and with an eye toward the acquisition of FLTSATCOM, a parallel program was pursued leading to the design and procurement of tactical shipboard receivers. The rapid procurement of terminals was enhanced by the nature of the GAPSAT lease. Although yearly fees were high for the leasing of the wide and narrowband channels, these costs were much lower than the total satellite purchase price would have been in the first several years of procurement. To support the half--duplex requirement of the Fleet Broadcast (receive only) aboard ship, the Navy began purchasing the AN/SSR--1 satellite receiver system. The SSR--1 accepts transmissions between 240 and 340 MHz with a PSK modulation bandwidth of 25 KHz,

and demultiplexes an input of 1200 bps into 15 output channels at standard teletype speed (75 bps).

The receiving set consists of 4 separate units each containing: an antenna, an amplifier--converter unit, a combiner--demodulator unit, and a demultiplexer unit. Each antenna and associated equipment comprise one of the four identical channels in the system that produce a hemispherical receive capability. This receive technique results in an improved signal--to--noise ratio when more than one antenna is in view of the satellite. In summary, the system operates in a noisy environment and in locations where received signal levels are lower than normally considered practical.

3. Fleet Satellite Communications (FLTSATCOM)

The fleet satellite communication (FLTSATCOM) network provides worldwide high priority UHF communications among Navy aircraft, ships, submarines, ground stations, SAC (Strategic Air Command), and essential command networks and provides a Fleet Satellite Broadcast.

FLTSATCOM is the first operational system totally designed for the Navy's needs in a strategic and tactical environment. The main advantages of FLTSAT over GAPSAT are its individual transponders for

each satellite access and increased EIRP. FLTSATCOM has a four satellite constellation over the equator, positioned at 23° WEST (Atlantic), 100° WEST (Continental U.S.), 75° EAST (Indian Ocean), 172° EAST (Western Pacific). The FLTSATCOM satellite is considerably larger and heavier than a GAPFILLER satellite. The FLTSATCOM satellites themselves weight more than 4000 lbs (1860kg) at launch and more than 2000 lbs (912kg) in geostationary orbit. They consist of two principal components, a payload module and the spacecraft module, each with a basic 8--foot (2.44m) hexagonal body. The payload module contains UHF and X--band communications equipment antennae, with each of its six side panels carrying related communication components. The 16--foot (4.88m) parabolic UHF antenna is made up of ribs and mesh, and opens like an umbrella. There is also one helical UHF antenna and one SHF horn antenna (used for the up--link communications). The spacecraft module contains nearly all the other subsystem equipment, including the earth sensors, attitude and velocity control, telemetry, tracking and command systems, electrical power systems, and non-separable apogee kick motor.

The spacecraft is stabilized on three axes and its design life is five years. Each FLTSATCOM satellite has the capability to relay communications on

twenty three separate RF channels. There are ten 25 KHz channels, twelve 5 KHz channels and one 500 KHz channel for each satellite. The ten 25 KHz channels have been dedicated for use by the Navy. Each of the twenty three RF channels has three different frequency plans in which the uplink or downlink may be transmitted. This capability precludes interference at those points in which earth satellite coverage overlaps with the coverage of an adjacent satellite. The transmission data rates in the ten 25 KHz are not critical to satellite operation. Failure of one FLTSATCOM satellite channel would eliminate only one user communication network. The total RF power of the ten 25 KHz downlink channels is approximately six times the radiated output of the GAPSAT UHF channels. Power balancing of earth terminal RF output is not critical to satellite operation. The characteristics of the ten 25 KHz channels are as follows [Ref. 10]:

- 2 channels with an EIRP on each channel of 28dBw
- 8 channels with an EIRP on each channel of 26dBw
- Receive G/T -16.7dB/K
- UHF Antenna Coverage 17

The launch of the first FLTSATCOM satellite into a geostationary equatorial orbit over the United Stages was successfully made on February 9, 1978. FLTSATCOM--2 was orbited in May, 1979, placed initially

at 20W longitude, and then moved to 100° longitude. FLTSATCOM--3, launched on January 17, 1980, was placed at 23° W longitude (where FLTSATCOM--2 had previously been stationed). FLTSATCOM--4, launched on October 30, 1980, is positioned at 172°E longitude. These four satellites provide total earth coverage except for the polar regions. The fifth satellite, FLTSATCOM--5, was launched on August 6, 1981 to provide an in--orbit spare. It will ensure continuity of service in the event of failure of one of the other four satellites.

The subsystems that comprise the FLTSATCOM system are:

a. Fleet Satellite Broadcast Subsystem (FSB)

The FSB subsystem provides the capability to transmit Fleet Broadcast message traffic in a high level jamming environment. The subsystem has fifteen subchannels of covered message traffic at an input data rate of 75 bps per channel. These fifteen subchannels are time division multiplexed and transmitted in a one-way RF transmission at 1200 bps. The shore based terminal transmits these data on a direct sequence spread spectrum SHF signal to the FLTSATCOM or LEASAT satellite, where the signal is translated to UHF and down-linked to the subscribers.

b. Common User Digital Information Exchange Subsystem (CUDIXS) / Naval Modular Automated communication System (NAVMACS)

This subsystem is divided into two major elements: CUDIXS and NAVMACS.

This program has been phased to address growth capability in existing installations and unique requirements of ships having a high volume of message traffic.

Collectively these two subsystems provide improved ship--to--shore and shore--to--ship operational communications. These communication improvements are directed toward increased message traffic through--put rates, increased traffic volume and improved link reliability. The subsystem is a functional replacement for the ship--to--shore itinerant ORESTES network.

c. Submarine Satellite Information Exchange subsystem (SSIXS)

The SSIXS is designed to complement existing communication links between shore stations and submarines. The subsystem provides, at the discretion of the submarine commander, the capability to exchange covered voice or message traffic via FLTSATCOM or GAPFILLER satellites with the shore operations control centers. One 25 KHz channel on each of the four

satellites has been allocated to SSIXS. The subsystem will support a network membership of sixty subscribers within a satellite footprint [Ref. 10 page 27]. The baseband equipment installations at the operations control centers have dual functions in collecting and transmitting message traffic: (1) Where broadcasts of message traffic are being made to operational units, the SSIXS baseband equipment routes the message traffic for transmission on the RF link and routes the same message traffic to the Integrated Submarine Automated Broadcast Processing System (ISABPS). The ISABPS processes and passes this message traffic for transmission on other RF communication links. (2) Between broadcast operations with message traffic, the baseband equipment at the operations control centers is used for receiving or transmitting message traffic.

d. Anti--submarine Warfare Information exchange Subsystem (ASWIXS)

The ASWIXS is designed to provide a communication link via satellite relay between surface ships, submarines, and Anti--Submarine Warfare (ASW) Operation Centers. This subsystem is unique in that the equipment provides for three different modes of operation:

(1) ASW Mode. In this mode, the link control design enables message traffic transmissions or voice communications between network subscribers on the same RF channel. One RF channel on each of the four FLTSATCOM satellites has been allocated for ASW Mode transmissions. The RF transmission data rate is 2400 bps.

(2) SSIXS Mode. When this mode of operation is selected, the submarine may operate as a subscriber to the SSIXS network. Surface ships, shore stations and aircraft having ASWIXS installations do not have the SSIXS mode feature available for use.

(3) Secure Voice Mode. There are two secure voice RF channels designated for voice communications. Only one channel may be selected at a given time.

e. Secure Voice Subsystem

The secure voice subsystem will enable, via satellite relay, the transmission of ship--to--ship, ship--to--shore, and shore--to--ship voice communications. The subsystem will transmit and/or receive secure voice communications via a half--duplex, push to talk satellite link. Two channels on each of the four FLTSATCOM satellites have been allocated for use by the secure voice subsystem. The subsystem employs digitized voice at a data rate low enough to be

compatible with a three KHz voice channel and therefore is listed as narrowband. This requires special processing of the speech signal at the handset terminal. The RF transmission data rate is 2400 bps.

f. Tactical Intelligence Subsystem (TACINTEL)

The TACINTEL subsystem is used for transmission of special intelligence communications. The subsystem is essentially a computerized message processing installation that enables receipt and transmission of message traffic via satellite under a controlled environment. The link control protocol for TACINTEL is similar to that of CUDIXS. One 25 KHz channel on each of the FLTSATCOM satellites has been allocated for TACINTEL.

g. Control Subsystem

The control subsystem has been structured to address control from the viewpoint of:

1. Sending and collecting system status information on the basis of a defined geographical area (satellite footprint) and on a worldwide basis.
2. Control of system resources, based upon demand, degradation of system capability, or use of emergency controls as a result of operational requirements.

4. LEASAT Satellite

The last generation of communication satellites for Navy use has been obtained on a leased basis, hence the program name, LEASAT. These satellites are a

replacement for the FLTSATCOM satellites. There is some commonality in design features between LEASAT satellites and the GAPFILLER and FLTSATCOM satellites. The LEASAT satellite have seven 25 KHz UHF downlink channels, one 500 KHz wideband channel and five 5 KHz channels. One of the seven 25 KHz UHF downlink channels is the downlink for Fleet Satellite Broadcast message traffic. The broadcast uplink is SHF with translation to UHF occurring in the satellite. The remaining six 25 KHz channels are operated as direct relay channels with separate repeaters. The Space Shuttle places LEASAT in a circular parking orbit at approximately 296 kilometers (160 nautical miles) altitude with 28.6 degrees inclination. They are then boosted into a circular orbit at 35,744 kilometers (19,300 nautical miles) over the equator within a 3 degree inclination.

The Navy operates the Fleet Broadcast channel with the same SHF spread spectrum uplink as in FLTSAT, and the six 25 KHz repeaters. It should be noted that there are four less 25 KHz channels on LEASAT, however, the actual number of accesses per channel have increased due to installation of Demand Assigned Multiple Access (DAMA) units in the LEASAT time frame. Each of the Navy relay channels are operated at a information rate of 2400 bps yielding a Bit Error Rate

(BER) of 10^{-5} with the LEASAT and shipboard terminal pairings.

Table III shows comparative data for EIRP and antenna G/T values.

TABLE III

DATA FOR EIRP--ANTENNA G/T VALUES

		Fleet Broadcast	Wideband	Relay	Narrowband
EIRP	dBW	26.0	28.0	26.0	16.5
G/T	dB/K	-20	-18.0	-18.0	-18.0

D. EVALUATION OF THE NAVY'S SATELLITE COMMUNICATION SYSTEM

1. Advantages

The GAPFILLER--FLTSATCOM--LEASAT communication satellite systems have already and will continue to provide extremely effective solutions to many of the unique problems inherent in Naval operations. Some of the advantages current communication satellite systems offer are:

a. Satellites are able to provide connectivity to and from geographically remote areas with few support facilities which may be subject to enemy hostilities.

b. In an era of political instability, satellite communications allow for reduced dependence on overseas communications sites.

c. Satellite communications connect widely separated members in the chain of command, rapidly and reliably passing a small volume of high--precedence traffic back and forth while retaining a proven capacity to pass a high--volume of low--precedence traffic.

d. Satellite communication systems overcome many of the platform constraints imposed by mobile platforms in which space and weight are at a premium, instability can be guaranteed, and communications are ancillary to the primary combat mission. Satellite communication systems currently in use require only small, grossly stabilized, antennas; light--weight, compact, and low--power transmitters and receivers; and are easy to operate and maintain.

e. Satellite communication systems reduce the probability of position intercept, reduce susceptibility to enemy intercept, and increase resistance to jamming.

2. Weaknesses

The satellite communication system is essentially a duplication of the previous HF communications systems without many of their weaknesses and disadvantages. However, the Navy's communications are still operating in a high use frequency band where relatively narrow bandwidths must be maintained.

Other weaknesses stem from the nature of the satellite communication systems themselves. Cost constraints led to decisions based on space segment

cost only and produced integrated, multi--function spacecraft which could become single--point targets for attempts at destruction or jamming by an enemy, or could produce significant degradation to the Navy's communications capabilities through single satellite failure. The integration of several requirements within a single spacecraft requires that satellite position become relatively inflexible and that replacement spacecraft be limited to virtual repeats of the same functions and capabilities as evidenced in the channelization scheme selected for the LEASAT system. The assumption of some of the long--haul communication requirements between major afloat commands and shore commanders by the Defense Satellite Communications System should help alleviate part of the problem.

3. Limitations on operation in the UHF band are:

Frequency congestion, lack of bandwidth, and inadequate jam resistance. The most significant disadvantage at EHF is its higher propagation losses, especially in heavy rainfall.

III. SATELLITE VULNERABILITY

A. INTERCEPTION AND JAMMING

The mission of the Navy requires that communications be maintained despite expected increases in intentional electromagnetic interference. The very successes of UHF satellite communication systems in minimizing detection due to emitter interception and in minimizing the intelligence value of the signals which are intercepted due to the increasing usage of online encryption, has made jamming a more promising alternative to a potential enemy. As the mobile users become less vulnerable to electronic warfare because of the capabilities of the satellite system, the satellite system itself becomes the target. Maintaining reliable communications in a jamming environment presents one of the most demanding challenges to the Navy's technology and resources at the present time.

B. JAMMING AND SIGNALS

Communication links can be jammed by two types of jammer: Noise jammers and repeaters. Noise jammers include all systems that generate their own signal. Repeaters are those systems using transponders and in which the communication signal is received, amplified, and retransmitted after processing.

Either of the above systems may be used to jam SATCOM via the uplink or downlink paths. The geometry is shown in Figures 3.1 and 3.2 [Ref. 14].

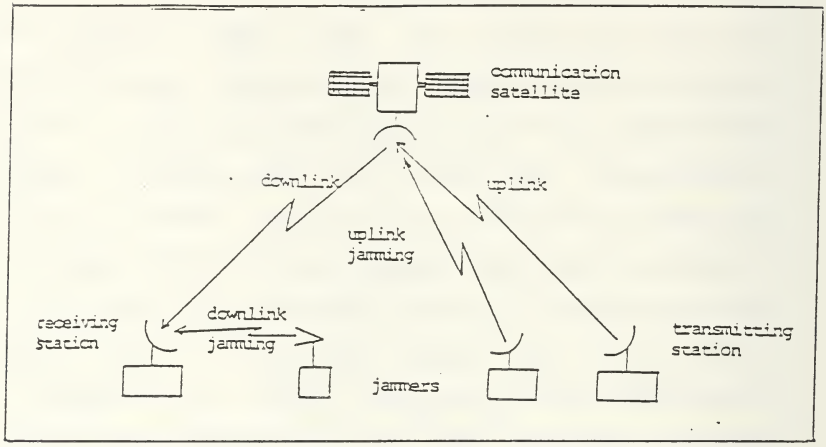

Figure 3.1 Jammer Geometry

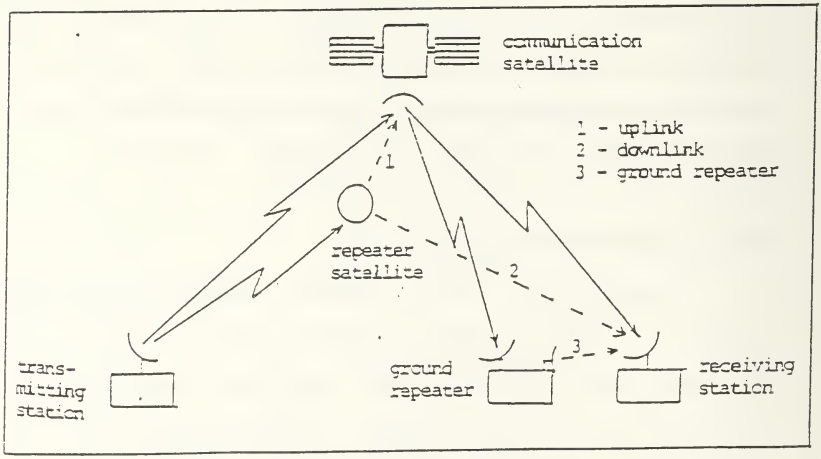

Figure 3.2 Repeater Geometry

The objective of a jammer is to obscure or deny information by masking or increasing the error probability of the detected data. Jammers can be classified according to the ratio of the jamming signal bandwidth to the communication receiver bandwidth. This ratio is smallest for the CW jammer. Initially, this appears to be quite effective, since all jammer power will be concentrated in the receiver bandwidth. However, notch filters may easily overcome CW jammers.

Repeater techniques: In these techniques the idea is to receive the communication signals, process them and retransmit. The difficulty is that the geometry required to effectively use repeaters is hard to achieve. In cases where the geometry is achieved one must carefully use the modulation or delay techniques. [Ref. 14] A straight repeater with no modulation is worse than no jamming at all, since it increases the signal power. Modulation, however, based on the target parameters, may be used to break synchronization in digital communication systems. Furthermore, repeater techniques have the advantage of being able to operate simultaneously against many links.

C. JAMMING OF LINKS USING FDMA/PSK

The main characteristics of the FDMA mode were discussed previously. Consideration of FDMA/PSK characteristics leads to the following conclusions [Ref. 14]:

1. Since there is no spreading, there is no processing gain, and the jammer requires no more Effective Isotropic Radiated Power (EIRP) than the signal. This will be much less power than in the spread spectrum case.

2. Each user uses, without overlap, a small portion of the total transponder bandwidth. This enables the use of narrowband jammers against some of the users without interfering with the others. Such use may have psychological effects on the jammed channels; for example, if the jammer operates only against some of the channels, the first reaction will be to determine if all the users have troubles. Since not all the users are jammed, the conclusion may be that something is wrong in the receiver.

3. PSK receivers generate their carrier local oscillator by processing the received signal through squaring loops. In the case of FDMA/PSK when there is no spreading process, these circuits can be denied by breaking the loop lock.

4. When comparing two jammers having the same average power, pulsed jamming is much better than continuous jamming.

D. JAMMING OF LINKS USING SPREAD SPECTRUM

A military communication satellite can be jammed, as we have already mentioned, on the up--link or on the down--link. Protection is generally obtained by using spread spectrum techniques: Frequency hopping (FH) or pseudo--noise (PN).

Frequency hopping works by rapidly switching the transmitter carrier over many channels within a very wide frequency band. Typically, more than 1,000 channels may be used and the switching rate can exceed 100 hops per second. Switching is controlled by a random code available to both the transmitter and receiver. FH is useful in heavily jammed radio environments because it is very difficult for the enemy to detect and follow the constantly changing frequency.

Pseudo--noise spread spectrum is obtained by multiplying the digital data signal by a much faster pseudorandom binary string. The resulting signal is transmitted over a wide band around a fixed--center frequency. Use of this technique decreases the probability of detection as the power density of the transmitted signal is divided by the spreading factor. If the spread is wide, it is possible that the transmission will have less power density than that of ambient noise at the site of an intercepting receiver. Protection against jamming is improved by the same factor.

FH and PN spread spectrum can provide a transmission protection in excess of 50 dB. The limitations inherent in these two techniques can be offset by combining their methods. Complementary techniques such as error detection and correction

codes, selective frequency rejectors, and adaptive antennas may be used to improve the basic performance of spread--spectrum techniques.

Error detection and correction codes are essential when data is transmitted in an environment containing high--power--pulsed jammers.

1. Frequency Hopping (FH)

In recent years, jammers have been getting smarter and faster at locating, identifying, and jamming a particular communication link. Frequency hopping offers an antidote. A leading technique for confounding narrowband, fixed--frequency jammers, frequency hoping results in short--duration transmissions that appear seemingly at random all over the bandwidth. Because an enemy cannot be certain when or where transmissions will take place, his jammers must constantly search the spectrum for the signal he hopes to jam. The jammer's effectiveness can be predicted quantitatively and displayed on nomograms for convenience in developing counter--countermeasures. The following equation will show how victim communications links can thwart enemy jamming efforts.

Jamming effectiveness depends upon relative signal strength, friendly on--the--air dwell time (DT), and the jammer's processing time (PT). For discussion

purposes, the jamming signal is assumed to be the stronger. PT is defined as the time from the target signal's first appearance to the time a jammer can direct energy against a victim receiver operating in that net. The formula for jammer effectiveness as a function of PT, DT and range becomes [Ref. 15]:

$$\% \text{ jammed} = \frac{100\,[DT - 2 \times 6.18\ \mu\text{sec/nm} \times \text{Range(nm)} - PT]}{DT}$$

Shortening the DT is a good method for defeating a jammer, because a shorter DT makes propagation delay significant and jammer--target ranges more critical. Even with an instantaneous PT, a jammer must be within 61 nautical miles to be 25% effective against systems with a one--millisecond DT. A more realistic 400--microsecond PT requires the jammer to be within 29 nautical miles, or well within the strike range of a naval task force. In effect, shorter dwell times decrease a jammer's effective range [Refs. 16, 17].

2. Pseudo-noise

Maximum admissible J/S at the input of an anti--jam (AJ) demodulator using PN direct sequence is given by:

$$(J/S)_m = \frac{W/2}{R(E_b/N_o)}$$

Where W = Spreading bandwidth (Hz)

R = Data rate (bits/s)

E_b/N_o = Energy per bit to noise density ratio (dB)

To increase the jamming resistance it is necessary to spread the signal over a wide band W, to reduce the information rate.

Higher frequencies (SHF or EHF) give more bandwidth W; however as the carrier frequency increases, demodulation becomes more difficult when information is transmitted at very low data rates due to the long term and short term stability (phase noise) of the local oscillators. This difficulty increases in case of mobile terminals.

PN spreading by direct--sequence over a W bandwidth is obtained with a code for which the chip duration is defined by $\delta = 2/W$; the autocorrelation function only exists on the $[-\delta , +\delta]$ interval. To obtain a continuous spectrum, the code period must be at least the inverse of the data rate; in fact in a military system an aperiodic code is needed to avoid action of an intelligent jammer. For a spreading bandwidth of 100 MHz, the signal exists only in a time segment of 40 ns (or 12 meters). This kind of spreading induces the need of a very high accuracy for localization and timing simultaneously.

E. UPLINK-DOWNLINK JAMMER

1. Uplink jammer

For a transparent repeater the protection ratio can be expressed by [Ref. 15]:

$$(J/S)_u = \frac{G_s}{G_j} (J/S)_m \frac{1}{L} \left[1 + \frac{Lp\ k\ W/2}{EIRP_s\ (G/T)_R}\right]^{-1}$$

Where $(J/S)_u$ = Jamming to signal ratio. Its a critical factor to estimate and trade off jamming effectiveness.

G_s = Satellite antenna gain in the signal direction

G_j = Satellite antenna gain in the jammer direction

L_p = Down-link free space propagation losses

$EIRP_s$ = Saturated satellite EIRP at beam edge

$(G/T)_R$ = Receiving terminal G/T

L = Limiter suppression factor

k = Boltzmann's constant = 1.38×10^{-23} J/K or -198.6dBm/K/Hz.

To improve the up-link $(J/S)_u$ it is necessary: (a) to use a satellite reception antenna with a very high directivity, and (b) to concentrate the power radiated by the satellite in the direction of the small terminals to have the condition $EIRPs(G/T)_R >> L_p\ k\ W/2$

For on-board AJ processing the protection ratio is only defined by:

$$(J/S)_u = \frac{G_s}{G_j} \times \frac{W/2}{R(E_b/N_o)}$$

2. Downlink jammer

The admissible jammer EIRP on the down--link is given by:

$$J = EIRP_s \frac{G'_s}{G_j} \times \frac{d_j}{d_s} (J/S)_m$$

Where G'_s = Antenna gain of the terminal user in the satellite direction

G_j = Antenna gain of the terminal user in the jammer direction

d_s = Distance to satellite

d_j = Distance to jammer

Generally, a jammer has an important distance advantage compared with a geostationary satellite, but it can see only a very limited area. To protect the down--link, high RF satellite power, reduced coverage area, and a terminal with high directivity antenna are required.

IV. HELLENIC ENVIRONMENT

A. INTRODUCTION

Hellas is a European country. The territory of the present Hellas was formed in the course of the last 150 years. It does not correspond exactly to the ancient Hellenic world; nor does it include all the regions inhabited by Greeks. But within the actual frontiers--an area consisting of wide variety of natural features--a very homogeneous state has grown up.

Bounded in the north by continental mass of Balkan Europe, its frontiers extend for 1166 Km, along the Albanian, Yugoslav, Bulgarian and Turkish borders, at a latitude of 41° 44' N. The country occupies the extreme end of the Balkan peninsula. Tapering off gently in a southern direction, the land mass then emerges out of the sea in a series of islands (3100 approximately), of which the most southerly, Gavdos (South of Crete), is situated at a latitude 34° 47' N strategically located in the middle of the Mediterranean. The distance from North to South is 771 Km (416 miles), that from the most easterly point, the islet of Ypsili, near Castellorizo, to the western point of Corfu 990 Km (535 miles). Only a small part of the rectangle enclosed in this area, barely one sixth, is actually occupied by land. The area of

Hellas is 132,561 sq. Km. In addition to the land frontiers, there are about 15,000 Km of coastline.

B. TECHNICAL CONSIDERATIONS FOR A SYNCHRONOUS COMMUNICATION SATELLITE

In designing a satellite communication link there are many interrelated factors to be considered, such as:

1. Choice of frequency for the link.
2. Numbers of channels to be linked.
3. The bandwidth requirements of the traffic and bandwidth capabilities of the important link elements.
4. The required transmitting power at the ground stations for the uplink, as well as the transmitting power at the satellite for the downlink.
5. Directive gains of antennas, the important loss parameters, and the performance margin requirements of satellite uplinks and downlinks.
6. The required earth surface coverage, or footprint of the satellite transmitting and receiving antennas. In the following example I will do some calculations to investigate a proposed requirement for a satellite system which will be used in the Hellenic environment.

Satellite power availability from the solar panels and other technical considerations (number of antennas, etc.) will dictate how many such programs could be shared via a single satellite.

C. UPLINK AND DOWNLINK CALCULATION

A satellite is capable of communicating with an earth station using a global coverage antenna if the station is in the footprint of the satellite. The problem of coverage angle and slant range is shown in Figure 4.1 [Ref. 18]. (The most of the following calculations are from refs. 2 and 18).

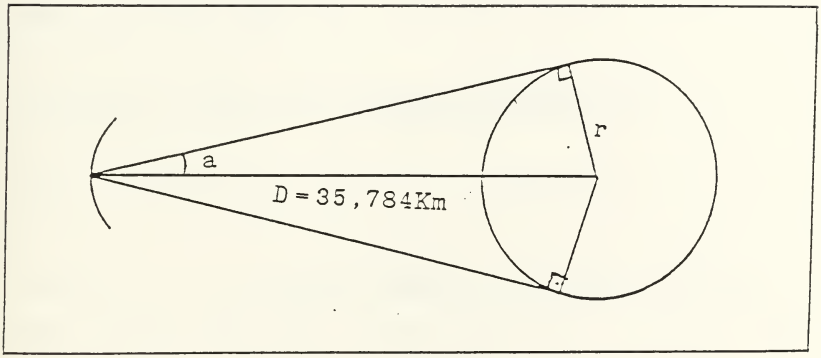

Figure 4.1 Hellas coverage angle and slant range

From geometry :

$$\sin a = \frac{r}{D}$$

If we need a coverage of total Hellas then

$$r = 535/2 = 267 \text{ miles } (495Km)$$

For a geostationary satellite :

$$D = 35,784Km$$

$$\text{so} \quad \sin a = \frac{495}{35,784} = 0.0138 \text{ radians}$$

or the coverage angle :

$$a = 0.79$$

The field of view (Ω_{fv}) is :

$$\Omega_{fv} = 2\pi(1 - \cos a) = 2 \times 3.14 \ (1 - \cos 0.79)$$

$$\text{so} \quad \Omega_{fv} = 6.01 \times 10^{-4} \text{ steradians}$$

Assuming an elevation angle > 5

Then θ which is the angular radius of the satellite footprint (Figure 1.1) and is:

$$\theta = 90 - E - a = 90 - 5 - 0.0138$$

so $\theta = 84.98^{\circ}$

The slant range d which is the distance from Hellas to satellite is:

$$d^2 = (r+H)^2 + r^2 - 2r(r+H)\cos\theta$$

$$d^2 = (495+35784)^2+495^2-2x495(495+35784)\cos 84.98$$

$$d^2 = 1.316 \times 10^9$$

and $d = 36297$ Km

Yielding a satellite round trip delay of

$$2d/c = 0.242 \text{ sec}$$

where c is the speed of light = 2.997925×10^5Km/s
The antenna gain for circular aperture is [Ref. 17]

$$G = \eta \frac{\pi^2 \times d^2}{(\lambda)^2}$$

where η = Antenna aperture efficiency (< 1)

d = Antenna diameter (m)

λ = Radiation wavelength = c/f

But because

$$G = \frac{4\pi}{\sigma_{fv}} = \frac{4 \times 3.14}{6.01 \times 10^{-4}} = 20909.1 \quad \text{or } 43.2 \text{ dB}$$

$$d^2 = \frac{G(\lambda)^2}{\eta\pi^2} = \frac{20909.1\ (1.403 \times 10^{-3})}{0.85 \times (3.14)^2} = 3.49$$

and finally

d = 1.87 meters or 6.17 feet

Figures 4.2 and 4.3 show calculations for uplink and downlink signals including jamming. To better understand the whole concept, I will use numbers which are close to the Hellenic environment. (All the concept and calculations are from Ref. 18)

Rb = Bit rate = 60 Mbps

Pt = Transmitted power = 5Kw

Gt = Transmitted antenna gain = 69.8dB

d_{ia}= diameter = 60ft

D = distance = 35,784Km

f_{cu}= Uplink carrier frequency = 8.09KHz

f_{cd}= downlink carrier frequency = 7.365KHz

Gr = Satellite antenna gain = 40dB

Gt = Uplink jammer gain = 60dB

Pi = Jammer's power = 10Kw

D = Jammer's distance = 300miles

Tsys=System's temperature = 1268K

G = Transponder's gain =70dB

TWTA = 40W

Gt = Satellite transmitted antenna gain = 30dB

Gr = Earth antenna gain = 69.8dB

G/T = 37dB

B_T = Transmission Bandwidth = 60MHz

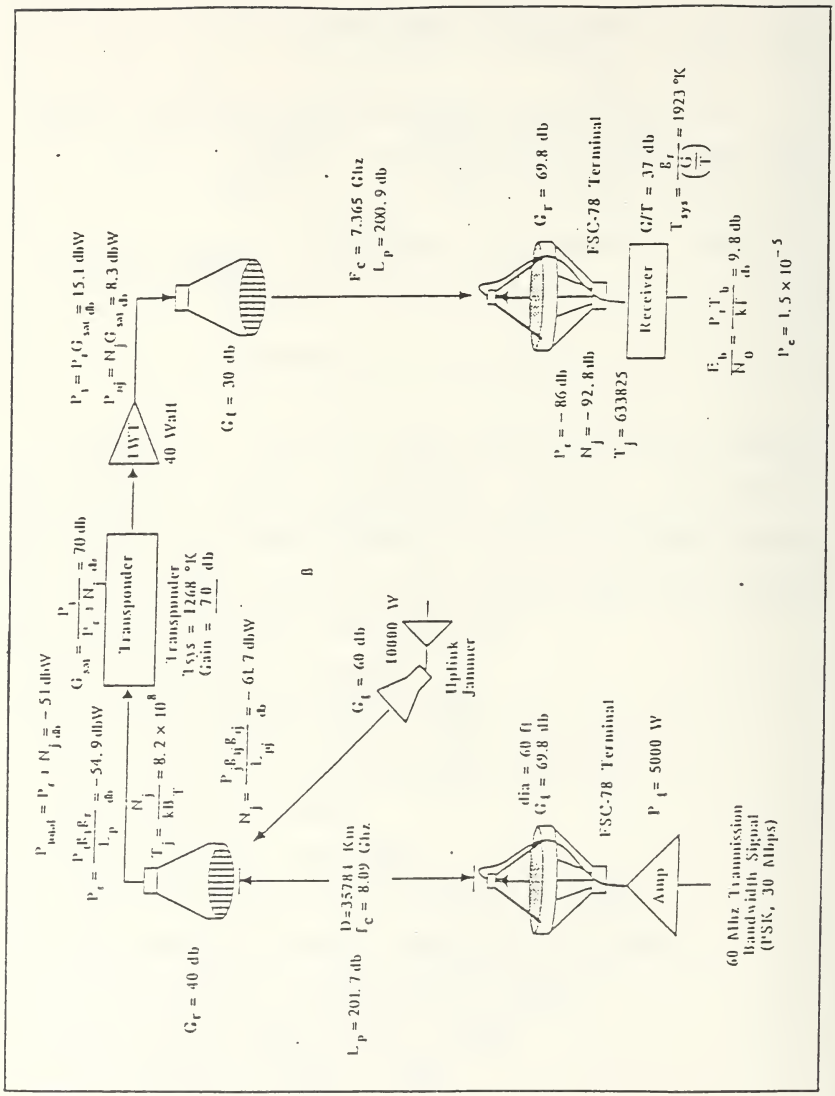

Figure 4.2 Uplink calculations

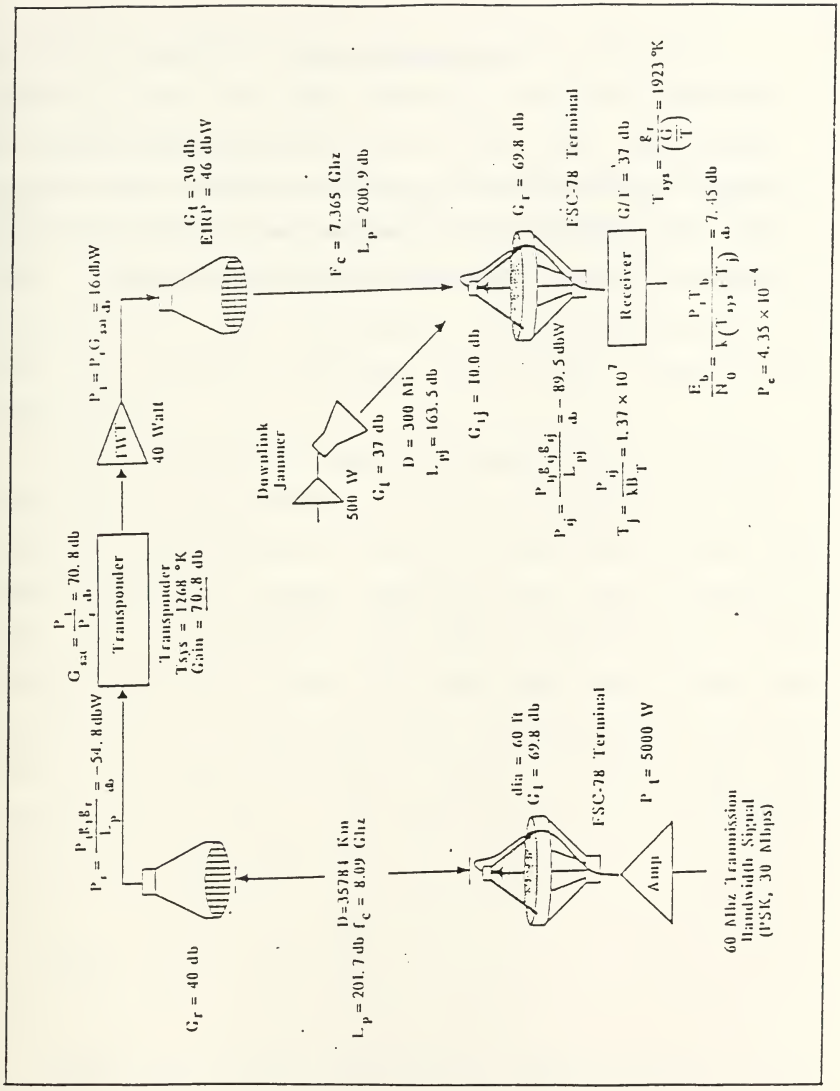

Figure 4.3 Downlink calculations

By using the results of the Eb/No at the earth station's receiver antenna when we have jamming to uplink and the Eb/No at the same receiver antenna with jamming to the downlink, we can conclude that is easier and more effective to jam the downlink than the uplink using the same jammer from the same distance.

V. COST EVALUATION

A. ECONOMICAL MODEL

When we say Fleet satellite communications we mean basically communications with mobile terminals. Up to this point we have discussed only technical characteristics and problems. In this section I will describe economic problems and will reach some conclusions.

If we are going to have systems dealing with mobile terminals in large numbers, then we can expect that these terminals will be small. It is the technology and economics of large systems with small terminals that is conspicuously the most interesting for the coming decades. Ref. 31 has indicated that the determinants of satellite cost are dependent upon the desired carrier--to--noise ratio (C/No) and the coverage area (A_{cov}). The exact relation is indicated in the following equation:

$$A_{cov} \left(\frac{C}{N_o}\right) = k \, P_T \, \frac{D^2}{T_s}$$

where A_{cov} = Area covered by antenna beam on the earth.

C / No = Carrier to noise density ratio - a measure of the ultimate information capacity of the channel regardless of how much bandwidth is used.

P_T = Transmitted power

T_S = System temperature at receive end of link

D = Diameter of earth station antenna

k = Boltzmann's constant

It is noted that the area to be covered on the ground and the basic information rate desirable in the system, are seen on the left side of the equation and the right side of the equation contains the physical size of the earth station antenna, the transmitted power in the either the earth station or satellite, and the corresponding system temperatures depending on which link is being considered.

The right hand elements of equation correspond to the items that determine the cost of a terminal. The transmitted power and antenna size are obviously important to the cost and, to a lesser extent, the downlink receiver temperature, although one can expect the usual progress in technology, and adequately sensitive receivers for lower costs. In broadcasting and other applications where the downlink typically limits the performance, it is necessary to trade satellite transmitter power against station size,

recognizing that the coverage is determined by the operational requirements.

Since there are many earth stations and only one satellite, the tradeoff should be made on a cost basis. As the satellite power goes up, the cost of the earth station goes down and there is an optimum set of characteristics to minimize the total system cost. In some applications, such as INTELSAT and other commercial systems, this may not be so important since the space and earth station costs come out of separate pockets. In the case of a military application, this kind of optimization is extremely important and unfortunately it is not often done. As an interesting aside note, the satellite altitude, carrier frequency and bandwidth are not involved in the first cost approximation. The figure--of--merit (G/T) also does not appear. It is the physical size, and not the gain of an antenna that is decisive.

An important point is that often the coverage area is fixed by operational requirements, but the total coverage area does not have to be served simultaneously. In other words, it is possible to switch the power from one beam to another or equivalently to move one beam consecutively to different locations to reduce the area covered from the point of view of the RF links while at the same time

maintaining adequate operational flexibility. This can result in a tremendous improvement in performance at an increase in space segment costs reflected in larger antennas, beam switches, and logic. Nonetheless, for the reasons mentioned, it will be worth the effort by reducing the total costs.

An analogous effect takes place in those systems in which the uplink limits performance. Rather interestingly, again it is the physical size of the earth station antenna which must be traded off against the receiver sensitivity in the spacecraft. In this case, however, it is more difficult to achieve really low system temperatures. There is not much improvement when the spacecraft antenna "looks" at the earth with its 290K temperature and attempts to get improved system temperature by lowering receiver noise temperature. Nonetheless, the coverage factor is the same as on the downlink and again, the use of multiple narrow beams on receiving links will considerably improve the performance of the system.

It is important to note that again the multiple beam or single switchable beam idea is dependent on the operational requirement that all of the area does not have to be served simultaneously but can be served consecutively either in a programmed or random fashion. This is not always the case, and if it is not, there is

no advantage whatsoever to the use of multiple beams. In the case of Hellas, one beam is enough to cover the global area from a geostationary satellite so the cost is lower.

B. LAUNCH COST AS A FUNCTION OF WEIGHT

Some factors affecting the satellite's launch cost are the orbital altitude, payload weight, and satellite size. The DSCS--II satellite has a beginning of life (BOL) weight of 500Kg. The launch vehicle for DSCS--II was the TITAN--III C. In 1970 the launch cost for a TITAN--III booster depended upon its payload. Prices started at $8.4 million for 455 Kg and went up to $18.1 million for 1364 Kg.

Using existing chemical rocket technology, it currently costs between $4000 to $10,000 per kilogram to ferry payload mass into low earth orbit via space shuttle [Ref. Cramer:Aug.1987]. This translates into a shuttle launch cost for DSCS--III between $2 million to $10 million.

The loss of the Challenger Space Shuttle in January 1986 left a void in the United States' satellite launch capability. This void is rapidly being filled by other nations, primarily by the European's Ariane booster and the Soviet Union's Soyuz and Proton rockets. At the 1986 International Aeronautical Federation (IAF)

meeting in Budapest, representatives from the Soviet Space Agency, Glavcosmos, announced that they would provide launch services to other nations via the SL--4 Soyuz and the SL--12 Proton rockets, at a cost of $5.7 and $28.5 million respectively. The Europeans on the other hand are charging $80 million per launch for the Ariane booster [Ref. Stine Nov '87].

C. COST EFFICIENCY MODEL

While the total development costs for communication satellites has increased, the cost per circuit--year has gone down with time. In 1984 Dr. Namkoong performed a statistical analysis on 13 series of commercial communication satellites to determine the primary factors that influence cost efficiency over time. The data was pertinent only for mature technologies and for existing active satellite systems. He did not include in his sample the first of a new series of satellites due to the high development costs involved with a prototype system [Ref. Namkoong].

The primary variables taken into consideration were the satellite's beginning of life (BOL), weight, and bandwidth--year. This is defined as the amount of bandwidth used by the satellite over its expected design life.

The general telecommunications cost model which was developed by L.W. Ellis and later modified by Namkoong is depicted in equation:

$$C = K\, e^{[-\delta(t-t_o)]}\, X^a\, V^c\, D^d$$

Where C = cost, is the annual exponential rate of technological change, X = capacity, D = distance, and V relates to the efficiencies gained by changes in the slope of the learning curve through increased production runs. The exponents a, c, and d are indicative of the economies of scale while K is an unspecified constant. Finally $t-t_0$ represents the time in years from the first procurement.

VI. DEVELOPMENTAL DECISIONS

This thesis has traced a general satellite overview and the actual development of the Navy satellite system. From a manager's viewpoint, some of planning decisions must be made along the way by both industry and Navy officials. These decisions based on both financial realities and the known technology base, contributed directly to the characteristics of today's system.

The three major decisions for a tactical satellite system involving one for the Hellas' Navy are:

1. UHF carrier frequency vice SHF
2. Active satellite instead of passive
3. New technology (Laser)

A. UHF VS SHF

Probably the most difficult and involved decision having the most profound effect on the Navy satellite system is the choice of up and downlink bands. From the purely engineering standpoint, SHF offer the most benefits but at the highest cost. As with every large defense procurement program, detail cost/benefit analysis have to be developed for UHF vs SHF systems.

At the present time, there are four frequency bands available for use by the Navy for general purpose

SATCOM which are consistent with the international frequency allocation structure. These bands are presented in Table IV [Ref. 19].

TABLE IV

FREQUENCY BANDS

	Downlink	Uplink	Nominal width
UHF	240 - 328.6 MHz	335.3- 399.9	90 MHz
SHF/X BAND	7.25 - 7.75 GHz	7.9 - 8.4 GHz	500 MHz
SHF/K BAND	20.2 - 21.2 GHz	-	1000 MHz
EHF/Ka BAND	-	& 30 - 31 GHz	1000 MHz

Table V compares these bands in areas of prime importance to a Navy tactical satellite system.

TABLE V

COMPARISON BETWEEN BANDS

	UHF	X BAND	K/Ka BAND
AJ capability	Poor	Good	Excellent
Low probability of intercept characteristics	Poor	Good	Excellent
Frequency sharing problems	Major	Minor	None
Cost	Moderate	High	Very High
Maturity of technology	Excellent	Fair	Poor
Atmospheric effects	Modest	Of some concern	Major concern

The earliest satellites utilized SHF for both the ground and space segments, relying on huge parabolic dish antennas on the earth to compensate for the weak satellite transmitters. Once enhanced power sources and miniaturization technology ameliorated the size and weight constraints, UHF equipment could compared on a more equal basis with SHF.

The downlink space loss at UHF is approximately 25 dB less than at SHF, based on path loss as a function of frequency:

$$Lp = \pi 4 f^2 D / c^2$$

Therefore, the required gain of a UHF ground terminal can be much less than at SHF. Conversely, highly effective jammer nulling techniques coupled with high antenna directively are more practical at frequencies above UHF. A 4--degree beam at UHF must utilize a 60 foot parabolic antenna whereas at SHF only a 2 foot aperture is required for the same beamwidth given equal gain.

Feasibility studies have been conducted using frequencies as high as 265 GHz for military SATCOM use. Atmospheric attenuation caused by humidity, clouds, and rain was found to decrease markedly as the earth terminal elevation angle increased toward the normal

(vertical position). For example, the estimated data rate at 30 degrees elevation exceeds that at 10 degrees by a factor of 4 at 21.2 GHz to a factor of 3000 at 265 GHz. For communication systems that operate in an all-weather environment, the higher the frequency, the more important it is to avoid elevation angles less than 30 degrees. Satellite/ground terminal geometry permitting high elevations (greater than 30°) has the additional advantages of negligible atmospheric scintillation, decrease vulnerability to detection, interference, and jamming. If SHF and UHF antenna sizes are equal, then UHF allows a much larger beamwidth which reduces the satellite tracking problem. Additionally, UHF offers lower equipment costs and generally higher transmitter.

The basic disadvantage of UHF is that bandwidth is limited. This limitation directly affects information capacity (data rate), usable frequency, and anti--jam capability.

The easiest approach for describing theoretical system capacity, C, as a function of bandwidth is through Shannon's formula [Ref. 26]:

$$C = B \log_2 (1 + S/N)$$

Where B = Bandwidth

S/N = Receiver signal to noise ratio

As available bandwidth greatly increases, as in the SHF band, so does system capacity as well as multiple access advantages. With narrow beam coverage readily available at SHF from the satellite, jamming is more difficult. A narrow beam, high gain antenna on a satellite permits a lower EIRP from the earth terminal thus lowering a tactical units probability of intercept at SHF.

The wide bandwidth available on SHF channels makes the use of spread spectrum even more powerful as an anti--jam technique. Certain platforms are severely limited in their ability to engage in a power contest with the jammer. These are the smaller platforms for which UHF is preferred over SHF; platforms which cannot utilize highly directive tracking antennas [Ref. 21].

B. ACTIVE VS PASSIVE SATELLITES

1. Introduction into PACSAT

The passive communication satellite is not an operational satellite system. PACSAT is a research project whose purpose is to design and evaluate a constellation of passive communication satellites. The project is sponsored by the Defense Advanced Research Projects Agency (DARPA) and is being conducted by the Rand Corporation [Ref. 22]. The proposed mission of PACSAT system would be strategic in nature and

categorized as being point to multipoint or broadcast in application.

The PACSAT is envisioned as being totally passive without any capability of amplifying or processing the received signal. In order to maintain its passive qualities, orbital stability will be attained by using the earth's gravity gradients. This will eliminate the need for the transmission of any corrective tracking, telemetry and control signal from the earth stations or the satellite.

PACSAT link configuration is shown in Figure 6.1 [Ref. 24].

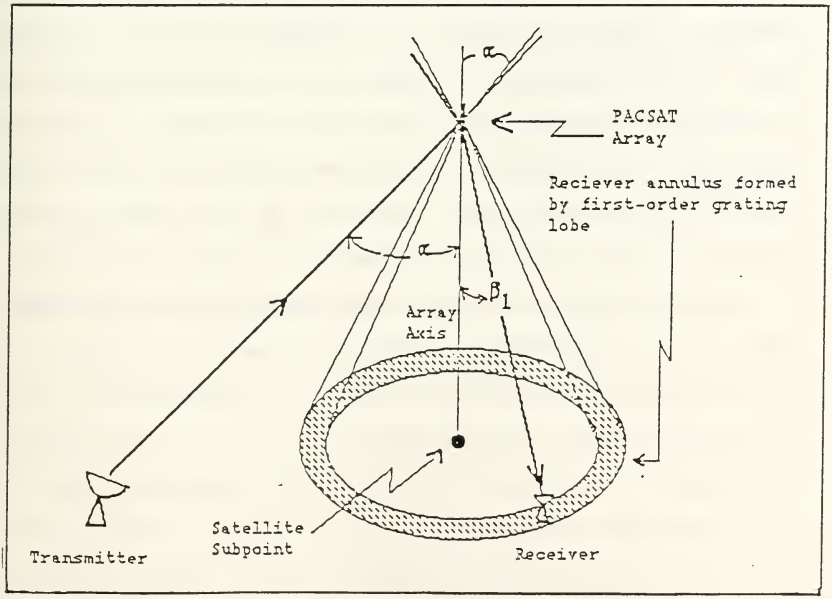

Figure 6.1 PACSAT link configuration

PACSAT will operate predominantly within the SHF frequency band with a nominal carrier frequency of 8 to 10 GHz. It will employ frequency hopping over a 360 MHz band of the communication spectrum in order to both steer the return signal and provide jamming resistance. The signal which is returned by the satellite is in the shape of a hollow cone or annulus. One is able to steer the annulus and thereby move the satellite antenna's footprint by selecting the appropriate frequency.

The satellite array consists of a long string of spherical scattering elements. Both the size and number of these elements are chosen so as to enhance the backscattering characteristics and therefore the directivity and gain of the entire array. The array may vary in length from 154 meters to 1.5 Km. It may be divided into as few as 100 or as many as 1000 sections, each of which is about 1.5 meters long.

The altitude at which the satellite is placed in orbit will depend upon several factors:

1. Acceptable signal loss due to propagation
2. Desired area of coverage
3. Number of satellites within the constellation
4. Propagation time
5. Satellite tracking capabilities of intended earth receivers

The predominant criteria for a passive communication system is the amount of propagation loss which may be sustained without reducing the communication reliability. Because of this, PACSAT will not be in geostationary orbit and will most likely operate at an altitude of between 6,000 and 10,000 Km. The rate of transmission will be predicated upon the acceptable bit error rate for the received message. Generally the slower the transmission rate the better the quality of the received signal.

2. Active satellite vs PACSAT

Due to advances in electronic miniaturization, increasingly more complex on board signal processing capabilities have been incorporated into active satellite designs. The increased capabilities of active satellites have increased the required complexities of earth bound receivers while at the same time reducing the per circuit--year operating costs.

These advances have not come without cost. Due to the sensitivity of the electronic components, the satellites have had to be hardened both physically and electronically so as to survive in a hostile environment. Passive satellites, due to their simple design, are less susceptible to physical attack than their active counterparts. Additionally a high

altitude electromagnetic pulse will not incapacitate a passive satellite.

Uplink jamming is a significant concern for active satellite systems. Not so for passive satellites. Because a passive system does not amplify the received signal it will not be susceptible to saturation or intermodulation of the Traveling Wave Tube Amplifiers (TWTA). The circuit elements are basically linear and hence resistant to uplink jamming.

Due to the absence of active components, the PACSAT system enjoys the advantages of simplicity, economy, survivability, and reliability. Additionally since there are no active components to wear out or to degrade as a result of radiation damage the passive system should experience an extended operational life.

One of the most significant disadvantages for any passive communications satellite is the weakness of the returned signal. This reduced signal strength will affect the design of the satellite's orbit, area of earth coverage and the speed at which the message may be transmitted.

C. LASER COMMUNICATIONS

Laser communications are not so different from other communication systems. There are basic properties of the laser which makes it attractive for

military communications. The short wave length and directionality of the laser makes it an inherently secure vehicle for military communications. Not only are small antennas and narrow angular divergences a benefit, but the resultant narrow field--of--view precludes acceptance of unwanted spurious or injected signals.

The natural advantage of a satellite platform enhances the laser's capabilities. Long communication distances are a result, and when geosynchronous orbits are used, long periods of visibility are available reducing the number of satellites needed and their expense. In fact, coupled with the laser's high data rate, satellite communications can effectively be covert.

Huge data capacity is in fact one of the most attractive advantages of laser communications. Engineering feasibility models have demonstrated a capability of transmitting 1000 Mbit/s of information over 40,000Km with a bit error rate of 1×10^{-6} and a SNR of over 9dB [Ref. 25].

On the negative side, lasers are not without their problems. Prime among these is atmospheric attenuation. Clouds and rainfall cause spread which results in smear and pulse lengthening. Apparently these effects can be lessened at the expense of data

rate. This is a very serious problem affecting the laser's acceptability for military communications. An alternative or backup approach would be use of multiple ground stations and satellite--to--satellite laser relay of information to one that can find a hole in the weather. Laser relay to a conventional communication satellite for transmission to earth is also possible.

Critical to the success of laser communications is acquisition by the receiver of the laser beam. Because of the narrowness of the beam, acquisition, particularly from space, is an extremely hard problem to solve. To accomplish the pointing accuracy required (less than one microradian), a laser beacon at each terminal will be used for acquisition. The system effectively operates like a radar where a wide beam is used for initial acquisition and is progressively narrowed until final acquisition is accomplished.

D. CONCLUSIONS

As modern fleet requirements become more complex and diversified, the role of Naval communications must expand to meet these new needs. Just as distance limited communications by signal flags, and flashing light was nearly terminated at the beginning of this century in favor of radio frequency communications,

today's satellite systems threaten to eliminate all other forms of communication.

From the earliest testing of moon and other passive satellite relays, the intent has always been to improve the efficiency, reliability, and capacity of the command and control channels which link the highest echelons of authority to the individual commanding officers at the scene of action. With each new generation of satellites, communication capabilities have been improved. Once the basic technological problems of data transfer were solved with impetus from the commercial sector, military planners addressed related aspects of modulation and access techniques for secure military data transmission. The resulting FLTSATCOM system represents a significant milestone in military communications development, meeting or exceeding the fleet's data transmission needs.

In the future, however, technological improvements in system design and allocation, must be implemented in order to ensure the viability of FLTSATCOM in a multi--threat environment.

In the beginning of this thesis I mentioned the underlying purpose was an analysis of a basic UHF satellite system with primary emphasis on evaluation of the system and how effective and reliable it will be in a hostile environment. Unfortunatelly the space and

the time for an evaluation between different systems concerning the economical and technical characteristics is not enough and a more specific study for both characteristics is needed.

This research is inteded to be a basic study of UHF satellite systems. If someone needs to choose a satellite system, a more specific and detailed evaluation has to be done, concerning the specifications which are necessary for the security, reliability, and survivability under a hostile environment.

At the present state of satellite communications, any study made to expand the facilities and capabilities of present Hellas Naval telecommunication system should include both a technical feasibility study and an economical analysis of all viable alternatives:

1. Communication satellite
2. Local area network (improvement in HF)
3. Optical communication (Laser)
4. Some combination of the above.

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